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Evaluation of Robotic Systems to Carry Out Traverse Execution, Opportunistic Science, and Landing Site Evaluation Tasks

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Acronyms

API	application programming interface
ARC	Ames Research Center
ATC	Air Traffic Control
ATHLETE	all-terrain, hex-limbed, extraterrestrial explorer
ATM	Air Traffic Management
ATV	all-terrain vehicle
CCD	charge coupled device
COM	component object model
ConOps	concept of operations
COTS	commercial off-the-shelf
D-RATS	Desert Research and Technology Studies
DEM	digital elevation model
DPOF	digital print order format
EAMD	Exploration Analogs and Mission Development
ESA	European Space Agency
FFC	Future Flight Center
FOV	field of view
GE	Google Earth
GPS	Global Positioning System
HMMWV	high-mobility multipurpose wheeled vehicle (ie, a Humvee)
HMP	Haughton-Mars Project
HMPRS	HMP Research Station
HORSE	Human Operated Robotic Science Evaluations (Project)
IRG	Intelligent Robotics Group
ISECG	International Space Exploration Coordination Group
ISS	International Space Station
JPEG	Joint Photographic Experts Group
JSC	Johnson Space Center
KML	keyhole markup language
LaRC	Langley Research Center
LER	lunar electric rover
LIDAR	light detection and ranging
LOLA	lunar orbiter laser altimeter
LRO	lunar reconnaissance orbiter
LROC	lunar reconnaissance orbiter camera
LSV	landing site validation
MI	Mars Institute
MMAMA	Moon/Mars Analog Mission Activities (Program)
MY	million years
NAC	NASA Advisory Council
NRC	National Research Council
NRCan	Natural Resources Canada
OSP	opportunistic science protocol
OSP-H1	opportunistic science protocol-Hypothesis 1

PI	principal investigator
PUP	power utility package
RF	radio frequency
SAIC	Science Applications International Corporation
SAR	specific absorption rate
SETI	search for extraterrestrial intelligence
SEV	space exploration vehicle
SMD	Structures and Mechanics Division
SPR	small pressurized rover
TRPF	traverse route planning and following
TRPF-H1	traverse route planning and following Hypothesis-1
TTL	through the lens
VBA	Visual Basic for Applications
WAC	wide-angle camera
XML	extensible markup language

1. Executive Summary

1.1 Introduction

This report covers the execution of and results from activities proposed and approved in Exploration Analogs and Mission Development (EAMD) Field Test Protocol *HMP2010: Evaluation of Robotic Systems to Carry Out Traverse Execution, Opportunistic Science, and Landing Site Evaluation Tasks*.

This research study was supported and funded as a collaboration between the Lunar Surface Systems Project Office (Code ZS) at the NASA Johnson Space Center (JSC), the EAMD Project at NASA JSC, the Intelligent Robotics Group (IRG) at the NASA Ames Research Center (ARC), and the Haughton-Mars Project (HMP) at NASA ARC and the Mars Institute.

The EAMD principal investigator (PI) is Stephen J. Hoffman, PhD (NASA JSC/ZS/Science Applications International Corporation [SAIC]), and the collaborating PIs are Matthew Leonard (NASA JSC/ZS) and Pascal Lee, PhD (NASA ARC/SST/Mars Institute/SETI Institute).

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1.2 NASA planetary surface exploration overview

The field tests documented in this report examine one facet of a larger program of planetary surface exploration. This program has been evolving and maturing for several years, growing from a broad policy statement with a few specified milestones for NASA into an international effort with much higher-fidelity descriptions of systems and operations necessary to accomplish this type of exploration.

In January 2004, NASA was placed on a new course when then President George W. Bush announced the Vision for Space Exploration (*A Renewed Spirit of Discovery*, January 14, 2004) that would return humans to the Moon by 2020 in preparation for eventual human exploration of Mars. By August 2005 the NASA Exploration Systems Architecture Study team had defined and characterized the basic transportation architecture for crew and cargo to accomplish these goals (*NASA's Explorations Systems Architecture Study*. Washington, DC: NASA Headquarters; November 2005. NASA Technical Memorandum 2005-214062). Near the end of 2008, it became clear that many space agencies were engaged in plans and preparations for missions beyond low-Earth orbit that could benefit from early coordination. As a result, the International Space Exploration Coordination Group (ISECG) was formed. In early 2009, the ISECG endorsed development of a Reference Architecture for Human Lunar Exploration and invited interested agencies to participate (Advancing the Global Exploration Strategy Human Exploration of the Moon. Summary of scenario discussions held by: International Space Exploration Coordination Group; March 10-12, 2009; Yokohama, Japan). To further the goal of cooperation, the ISECG established the International Architecture Working Group (IAWG) and the International Objectives Working Group (IOWG) to analyze

the lunar exploration objectives of participating agencies. A series of workshops conducted during 2009 led to the development of a set of common lunar exploration goals. These goals were accepted by the ISECG in December 2009. A set of strategic guidelines was combined with these goals to guide another working group in the development of a Reference Architecture that was adopted by the ISECG (*The ISECG Reference Architecture for Human Lunar Exploration – Summary Report*; July 2010. Available at: http://www.globalspaceexploration.org/home;jsessionid=00B68432DE6CEF02E137B2559276C6B1. Accessed September 16, 2011.).

The ISECG Reference Architecture is neither a lunar base nor a series of Apollo-style missions. It employs a flexible approach to lunar exploration that can accommodate changes in technologies, international priorities, and programmatic constraints as necessary. It relies on the NASA Constellation architecture for crew and large-cargo transportation but is robust to variations (increases or decreases) in landed mass. It also shows flexibility and redundancy will be improved by using small cargo launch vehicles to deliver scientific payloads and logistics (eg, laboratory and excavation equipment and crew support items such as food, water, and clothing). Finally, the ISECG Reference Architecture is composed of phases that will deploy a range of international human-rated and robotic technologies over time on the lunar surface. Moreover, it provides continuous robotic and human exploration activity in multiple locations on the Moon; these phases include:

- **Robotic precursor phase**: Provides early technology demonstrations and engagement among international partners, the scientific community, and the public. It highlights important activities intended to reduce the risks associated with human missions and to ensure sustainability of the architecture. These activities will also help target human missions toward the most promising objectives for scientific discovery and exploring Mars.
- **Polar exploration and system validation phase**: Initiates human exploration of the Moon. It leverages the robotic precursor work to deploy and test an international fleet of crewed rovers and supporting robots in preparation for more aggressive human and robotic lunar exploration. This phase builds up confidence in operations and systems design through a series of human missions at a given lunar polar site.
- **Polar relocation phase**: Relocates the fleet of robots and rovers, controlled from Earth, from the pole to new sites of interest. Along the way, this fleet will perform scientific studies and enable interactive participation from the public. Once in place, the fleet of robots and rovers will meet and assist human crews landing at these new sites.
- **Nonpolar relocation and long-duration phase**: May involve multiple short missions to various lunar sites of interest or long-duration missions of about 70 days at one site. Longer missions, which will require the addition of living modules or habitats, would be particularly useful for collecting data and testing technology for future Mars missions.

Questions that arose during the development of the "polar relocation phase" of this Reference Architecture addressed the impetus behind the field tests described in this report; ie,: What information and planning techniques are needed to safely relocate high-value assets across large distances of unexplored terrain without humans present? How much meaningful science and exploration can be achieved while making this traverse and still delivering these assets to the desired location on schedule? How can these robotic assets help to mitigate risks associated with landing in these new locations that will be faced by the human crews sent to explore these areas?

A specific scenario developed during formulation of the "polar relocation phase" of this Reference Architecture – an approximately 200-km traverse from the rim of Shackleton Crater to the Malapert Massif – was used to guide the development of the field tests described in this report. These field tests did not replicate this traverse in detail but took into account those features of the traverse (eg, transitioning across rolling terrain, using rock outcrops as waypoints and scientific targets, transitioning around the rim

of a crater, etc.) that were noted by the planners as they considered alternative means of completing their representative “polar relocation.”

1.3 Purpose of the study

The purpose of this study was to investigate several aspects of the polar relocation phase of the ISECG Reference Architecture for Human Lunar Exploration. It should also be noted that the results of field tests conducted for this study apply more broadly to the precursor phase of human exploration in a previously unexplored region of an extraterrestrial surface. In particular, this study examined the use of remote observation data and in-situ data for planning and execution purposes associated with robotically executed traverses, opportunistic scientific investigations, and landing preparations.

Several proposed planetary surface exploration scenarios, including the ISECG Reference Architecture, require that surface assets be robotically repositioned (ie, no crew on board but with human direction or oversight) from their initial location to a rendezvous location on which the astronauts will land at some time in the future. Several aspects require additional clarification or characterization for such scenarios.

1. Is the quality of remote observation data sets sufficient for effectively planning a route?
2. Is surface-level imagery (or other data acquired from the surface) a required augmentation to remote observation data for successfully completing a traverse?
3. Could multiple sources of surface-level imagery (or other data acquired from the surface) improve the efficiency of successfully completing a traverse?
4. How can opportunistic science be efficiently added to this type of traverse?
5. Can surface assets used to carry out a traverse also be employed to survey and return data sufficient to confirm those factors that lead to the choice of the proposed landing site?

In a specific scenario developed for the ISECG Reference Architecture, robotic and human-rated assets are relocated from a lunar outpost located on the rim of Shackleton Crater (near the lunar South Pole) to a location near the Malapert Massif on which a crew would land and rendezvous with the assets and use them to explore the Malapert Massif area.

The route being used to relocate the surface assets in this scenario would not have previously been explored and mapped at ground level. This scenario was selected as the specific example to be used as a basis to construct details of the three analog experiments carried out this year. It was also selected in part because we have access to remote data observations of our analog field test area that are similar to those likely to be available from the Lunar Reconnaissance Orbiter (LRO) or similar sensors.

1.4 Study hypotheses summary

The broad purpose of the study was condensed into six hypotheses that needed to be tested and could be done with the resources projected to be available during the 2010 summer analogs season (Table 1).

As indicated by the numbering of the following hypotheses, the study was implemented as three stand-alone, but related, experiments:

1. **Traverse Route Planning and Following (TRPF)**: Planning a traverse route plus alternate routing using remote observations of a quality similar to that typical of, or expected for, various planetary surfaces and carrying out the planned route using simulated imagery acquired from a surface asset to make key navigation decisions.
2. **Opportunistic Science Protocol (OSP)**: Planning and executing opportunistic science observations.
3. **Landing Site Validation (LSV)**: Validating the use of the robotic elements to survey a landing site for hazards.

Table 1. List of Hypotheses

ID	Hypothesis
TRPF-H1	The available remote observation data sets of a region to be traversed are sufficient for planning primary and alternate routes for the traverse.
TRPF-H2	Robotically implemented traverse route execution will require surface-level imagery to identify and maneuver around local hazards/obstacles.
TRPF-H3	Route traversing efficiency will improve in direct proportion to the number of surface-level imagery sources used to support a traverse.
OSP-H1	The amount of time needed to investigate the scientific characteristics of a target of opportunity is in direct proportion to the size of the target.
LSV-H1	The remote observation data sets available (defined in section 2.2.2) are sufficient for planning primary landing sites.
LSV-H2	Landing sites selected using remote observation data can be validated using robotic scout capabilities.

The study was separated, primarily for logistical reasons, into these three field experiments. Preliminary field test development for each of the tests indicated that a representative set of sensors likely to be found on the vehicles and assumed for this scenario would be needed. The minimum functional capabilities identified for these sensors included: (1) moderate- to high-resolution imagery for broad fields of view, (2) a companion capability for ranging within those broad fields of view, and (3) moderate- to high-resolution imagery for close-up inspection of objects. Recent field tests conducted for similar NASA analog missions indicated that a digital camera that was mounted on a GigaPan mount, a light detection and ranging (LIDAR), and a commercial off-the-shelf (COTS) digital microscopic imager would satisfy these functional needs. It was not practical, given the resources available, for this study team to obtain its own LIDAR, GigaPan, and microscopic imager as well as the corresponding infrastructure to support transmitting the data. The field test protocol was thus designed around having access to the HMP infrastructure as well as the NASA IRG and its K-10 robot being present at HMP during the 2010 field season. The field experiment approach needed to test the last three hypotheses (OSP-H1, LSV-H1, and LSV-H2) required the use of one of the HMP Humvees (or formally high-mobility multipurpose wheeled vehicle [HMMWV]), the IRG K-10 instruments, and the participation of K-10 field and operations teams. As it was impractical to have these assets available during the length of time needed to execute the traverse part of the study; it was decided to separate the examination of science objects from the traverse. Because the science objects were not necessarily part of the area to be evaluated as a landing site, it was natural to separate parts of the study that were needed to evaluate the OSP and LSV hypotheses.

Figure 1. Location of Devon Island and Haughton crater. Adapted from *National Geographic*. July 1999; 196(1):37. Permission obtained by Pascal Lee for use in NASA reports.

1.5 Experimental activities

The field study was conducted in the area of the Haughton meteorite impact crater on Devon Island (fig. 1) in the high Arctic, and implemented as part of the research activities of the 2010 field season of

the HMP. Field participants were based at the HMP Research Station (HMPRS) located at 75° 26' N, 89° 52' W (fig. 2), and conducted the reported investigations in a test area ranging from the research station base camp out to 10 km away.

The TRPF and LSV experiments were carried out in two major phases: the first, a traverse route or landing site selection phase using remote observation data, was followed by the second, a ground truth execution or validation phase during which various surface-level data sets were gathered from the planned traverse route and landing site for evaluation by planning teams. The OSP experiment required that specific targets be selected in the test area, so activities related to this experiment could not begin until the field team was at the test area. Table 2 documents the dates for these phases of the three experiments.

Figure 2. Haughton-Mars Project Research Station.

Table 2: Overall Schedule

Dates	Activity
5/18 – 5/21	Assemble the landing site selection team and select the location using remote observation data sets.
6/9 – 6/18	Assemble the traverse route planning team and select the route using remote observation data sets.
7/25 – 8/2	Gather on-site data. Photographs of the traverse route (TRPF) and of the landing site area and its hazards (LSV), as well as selection of science objects (OSP); plus the ground truth information of each.
8/3 – 8/5	Conduct traverse execution field test.
8/6 – 8/7	Conduct landing site validation field test.
8/7 – 8/8	Conduct opportunistic science field test.

A test area with the following characteristics was needed to provide a reasonable simulation environment in which to conduct the TRPF and LSV tests:

- relatively large area (many square kilometers), preferably free of vegetation, human-built obstructions (eg, fences, roads, etc.), or other ground cover (eg, snow, ice, etc.);
- terrain features and topography representative of the lunar South Pole region being simulated in these tests; and
- areas in which a traverse or landing could be successfully carried out as well as areas in which these activities could clearly not be carried out to determine the test teams' ability to distinguish between the two.

The region around the HMPRS (fig. 2) on Devon Island, Nunavut, Canada possessed these features, and therefore was selected for these tests. The relatively short field season budgeted for 2010 at the HMP site combined with the need for shared use of K-10 assets and the operations team support resulted in the somewhat compressed schedule of field events shown in Table 2.

During the field test phase, several different locations were used to receive and react to the data that were being sent from the test area. Most members of the TRPF planning team were located at the Future Flight Center (FFC) facility (fig. 3) located at ARC. This facility was chosen because if its ability to simultaneously display several large-format data sets (in this case imagery) for the planning team to evaluate. The European Space Agency (ESA) participant in this experiment was unable to travel to ARC so participated via a WebEx™ (Cisco Systems, Inc., San Jose, Calif) session and teleconference. However, this situation did have the benefit of simulating a physically distributed planning team that could be the eventual implantation of this function within the ISECG Reference Architecture. The OSP science team was made up of personnel also participating in the independent K-10 science activities at the HMP test area. Consequently this group participated from the IRG operations facility located at ARC. Finally, the LSV planning team was located at JSC (its home institution) for the field test phase of this experiment. Because of the small size of this team and short duration of this phase of the experiment, projection facilities at JSC (for the imagery data used in this phase) were considered adequate as compared to the logistics involved with using the ARC FFC facility.

Figure 3. FFC at ARC during the TRPF study.

Figure 4. Typical view on Devon Island.

The TRPF planning team consisted of William Carey (ESA), John Gruener (JSC), Jason Poffenberger (JSC/Wyle), and David Reeves (NASA Langley Research Center [LaRC]). Jason Poffenberger and David Reeves were involved in the detailed planning of a robotic traverse between Shackleton Crater and Malapert Massif that is the basis of this simulation. This team was given a set of eight way points, selected by Stephen Hoffman, that were designed to result in a traverse that would cover many of the terrain types seen on the Shackleton Crater to Malapert Massif traverse, including very flat terrain, rolling terrain, and crater rims (fig. 4). The team was also provided with a set of remote observation data comparable in resolution to the data expected to be gathered by the Lunar Reconnaissance Orbiter in the Shackleton Crater area. The traverse planned by this team was 23.8 km long (for comparison, the straight-line distance connecting the eight way points was 22.7 km long). Several alternate paths were planned around questionable terrain, and objects of potential scientific interest along this route were noted.

A remote satellite communication station (fig. 5), which was associated with this TRPF experiment, was set up to support activities outside the range of HMP base communications. This communication station was an adaptation of an Iridium Communications Inc. system that was initially designed for maritime use. Not only was testing of this system important for the TRPF experiment, it was also deemed important for other potential uses; eg, D-RATS [Desert Research and Technology Studies] or other yet-to-be-identified isolated analog test sites.

Figure 5. An Iridium OpenPort satellite terminal (Iridium Communications Inc., McLean, Va) deployed on Constellation Hill, Devon Island.

The OSP science team located at ARC consisted of Martha Altobelli (University of Texas/Austin), Josh Garber (University of California/Davis), Elizabeth Palmer (Case Western Reserve University, Cleveland, Ohio), and Tim Shin (University of Texas/Austin). A set of 11 science targets was chosen by Pascal Lee for the science team to investigate with the instrument suite available to them; for this experiment the instrument suite consisted of the K-10 rover, with its three instruments (GigaPan, LIDAR, and microscopic imager) mounted to the roof rack of the HMP Mars-1 Humvee Rover, which simulated a large, human-rated rover being driven robotically along the simulated Shackleton Crater to Malapert Massif traverse (fig. 6). These targets were

Figure 6. Humvee with K-10 on top.

chosen to cover the size range of interest for this experiment. Consistent with the test protocol, the science team was given relatively little information about these targets prior to using the instruments to conduct an investigation considered sufficient for a first-order characterization of these objects. The science team was provided with the location of each object, plotted on a map of the surrounding area, and one or two "approach" images showing each object as it would appear as a robotic rover came closer to it. At that point it was up to the science team to decide how best to investigate each object.

The LSV planning team consisted of Brian Derkowski (JSC), Doug Rask (JSC), and Alan Strahan (JSC), all of whom have supported systems or operations development for the Altair Project Office. This team was provided with the same data set as was provided to the TRPF team as well as a specified 1-km-diameter area in which the team was expected to identify a "safe" primary and at least one alternate landing site. This team used Altair vehicle tolerances and approach flight characteristics being carried at that time by the Altair Project Office to identify the candidate primary and alternate landing sites (fig. 7).

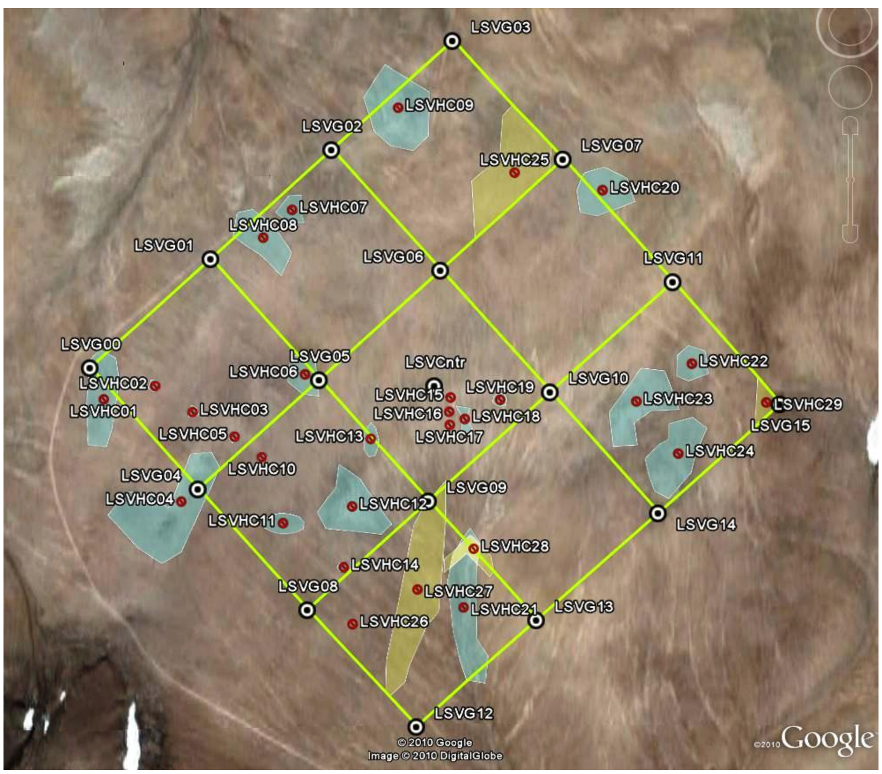

Figure 7. Landing site selected by LSV planning team. The light green areas are suspected hazards from the original visual inspection of the remote observations that were copied from the PowerPoint file into Google Earth. The light yellow areas are suspected slope hazards from analysis of the digital elevation model (DEM).

1.6 Results and lessons learned

We developed six hypotheses that we could test in the field for the three experiments conducted this year. Of these hypotheses, data collected indicated that four were true (TRPF-H2, OSP-H1, LSV-H1, and LSV-H2), one was not true (TRPF-H1), and one was not tested (directly) due to resources and time constraints (TRPF-H3).

The main lessons that we learned from the TRPF experiment were: (1) the assumed remote observation data are insufficient to plan a definitive route that is completely free from undetected obstacles that would stop vehicles of the type assumed here; and (2) while the remote observation data did not allow an obstacle-free route to be

planned, these data combined with the assumed sensor suite used by the robotically driven surface vehicles would have been sufficient to find a successful path around these obstacles.

The main lesson we learned from the OSP experiment is that the time required to investigate scientific targets of opportunity on the Moon using a small pressurized rover (SPR)-type vehicle in robotic mode will increase with target size scale, but not in simple proportion with size. While the sample set tested at HMP-2010 was small, preliminary data suggest that, in general, investigation time increases with target size scale following a power law. Potential variations are expected due to factors such as the inherent complexity and uniqueness of the targets, trafficability in the area immediately around targets, the makeup of the science payload, and lighting and viewing conditions.

The main lessons we learned from the LSV experiment were: (1) the remote observation data were sufficient to select an adequate landing site, with an alternate landing site adjacent to it, within the Altair constraints at this location; and (2) surface-level imagery significantly improved the understanding and confidence of the selected landing site as well as the nature of the potential hazards – ie, the primary and one alternate landing site could have been validated at this location.

One observation that we made in all of these experiments is the need for cues within the imagery to assist users in determining size, distance, and slope for the terrain in the image. An opportunity to partially test one of these cues – distance – using a LIDAR instrument was not feasible due to weather issues at the test site.

A lesson learned during the traverse experiment, but that has implications in all of the experiments, is the need to use planning tools that can integrate the various data sources and other meta-data used to provide planners and operators with better situational awareness as they plan or execute their tasks.

All of these conclusions and lessons learned are made with the caveats detailed in the following sections of this report. These sections also describe the data gathered and the process used to analyze these data to reach these conclusions. The raw data, images, and field notes for each of these experiments have not been included in this report due to volume considerations. However, these data can be obtained by contacting the PIs.

1.7 Future study recommendations

All three of these experiments were carried out for the first time this season. While the data collected were sufficient to draw conclusions for each of the hypotheses, additional data from additional test cases for each of the experiments could be used to improve statistical correlations (the OSP experiment) or to improve or refine procedures (TRPF and LSV).

For the TRPF experiment, in addition to more instances of planning traverses over diverse terrain, longer traverses (50 to 100 km or greater) should be planned and carried out. Adding visual cues for distance, size, and slope to the surface-level imagery presented to the “drivers” should also be included, and the improved efficiency of the execution phase should be noted. (Adding visual cues should actually improve all three experiments.)

For the OSP experiment, further field studies at Devon Island and elsewhere are recommended to better quantify the relation between science target-size scale and investigation time, and its potential variations. A three-pronged approach is suggested:

a) Conduct a dedicated experiment at Devon Island with a longer time baseline in the context of a simulated longer range (5-km +) robotic traverse.

b) Continue logging data opportunistically during rover field tests at Devon Island and elsewhere, which would then be used to update the results reported in this report.

c) For comparison purposes, begin examining at Devon Island and elsewhere the issue of time and operations support required for opportunistic science investigations in the context of a long-range (10- to 100-km +) crewed SEV traverse.

The planning tools developed for the TRPF experiment proved to be quite useful in accelerating the planning process, but use of these tools also provided insight into additional features and capabilities that would further improve their utility in the planning process as well as expand their use during the operational phases of a mission. Such improvements could be developed incrementally as part of a process of repeating these experiments, as mentioned previously. These tools should be discussed with the D-RATS as one possible means of improving the D-RATS traverse planning process.

2. Study Overview

2.1 Purpose

This section describes the field test protocol, as well as the facilities and equipment, used to test the six hypotheses described in section 1. This field test protocol describes three stand-alone but related experiments (TRPF, OSP, and LSV) that encompass these six hypotheses. Each of these experiments deals with one aspect of the "polar relocation phase" of the ISECG Reference Architecture in particular, but also with the precursor phase of the human exploration in a previously unexplored region of a planetary surface in a general sense.

To construct specific details necessary to carry out each of these experiments, a specific scenario is required. One scenario recently under consideration by NASA and the ISECG as part of the ISECG Reference Mission development is the relocation of assets from a lunar outpost on the rim of Shackleton Crater (near the lunar South Pole) to a rendezvous location near the Malapert Massif. This scenario was selected as the specific example to be used to construct details of the traverse, opportunistic science, and landing site validation experiments described below.

2.1.1 Traverse Route Planning and Following

The purpose of this experiment is to gather data that would be relevant to robotically repositioning surface assets used for planetary surface exploration from a previously explored location to a new location on which a later human exploration mission would rendezvous with these assets.

Using the selected analog scenario of a robotic traverse on the lunar surface from an outpost at Shackleton Crater to the Malapert Massif, the distance to be traveled would be approximately 200 km. The following assets would be moved: 2+ Space Exploration Vehicles (SEVs), 1+ mobile habitats carried on an ATHLETE (all-terrain, hex-limbed, extraterrestrial explorer), and 1+ Power Utility Packages (PUPs). A small number of robotic scouts may be useful to help navigate through known and unanticipated hazards as part of the operational concept for such a traverse.

As these are exploration scenarios, the route will not have been previously traversed and the only pre-traverse data sets available will be remote (orbital) observations. Because the route has not been previously traveled, it is also highly likely that there will be objects of potentially interesting science value along the traverse route and, thus, there will be a possibility of executing opportunistic science observations; ie, science observations that do not exceed the time and power available during the traverse.

A general description of the concept of operations (ConOps) that would be used for this type of traverse can be summarized as follows:

- A route planning team, with input from vehicle engineers, operator/drivers, and scientists, will use remote observation data to plan a "safe" route between start and end points (ie, there are no apparent obstacles or hazards that would prevent any of the vehicles that are being moved between these points from completing this route) that is to be completed within a specific period of time.
- The human drivers for this "convoy" will use imagery (and potentially other data) obtained from the surface to confirm the safety of this route as these vehicles move along the planned route. These data are assumed to be acquired by the lead vehicle in the convoy, regardless of the platform used. If an obstacle or a hazard is encountered that was not detected by remote observation data, this lead vehicle will be used to find a "safe" route around the obstacle/hazard. The rest of the vehicles will hold position until a "safe" route is found and then follow that "safe" route.

In general, what we are trying to test are approaches to:

- Maximize the amount of resources (time, power, etc.) available for science by minimizing the resources needed to maneuver across the surface within a specific period of time.
- Test alternative approaches to accomplish key features of a robotic traverse of this type.

2.1.2 Opportunistic Science Protocol

If the robotic prepositioning traverse described in the previous section becomes the normal method of moving surface assets across the planetary surface, these traverses will open up a large amount of otherwise unexplored planetary surface terrain to exploration. Such traverses will likely pass near sites, which may represent important science opportunities for the science community, that may not be visited by an astronaut crew. It is important to determine what opportunistic science could be accomplished by robotic assets on such a traverse and whether additional science investigation capabilities should be added to the traverse, and also to have metrics to determine the cost in time and other resources for carrying out the opportunistic science.

In general, what we are trying to determine is:

- Will we be able to provide decision makers with reliable estimates of the time and other resources required to investigate science targets of opportunity?
- What factors determine the operational impact of conducting opportunistic science?
- How do we maximize the amount of opportunistic science achieved in the course of a robotic traverse that is driven and constrained primarily by nonscience objectives?

2.1.3 Landing Site Validation

The purpose of this field study is to gather data that may help determine whether selected landing sites that use remote observation data can be validated using robotic scout capabilities on the surface.

The current lunar lander concept is designed to be capable of landing at a site with a 6-deg mean slope and some combination of the following:

- A 1.4-m-tall rock under one of its footpads
- A 1.4-m-deep crater under one of its footpads
- Some combination of rock/crater that falls within the two boundaries

Figure 8 illustrates these surface feature constraints.

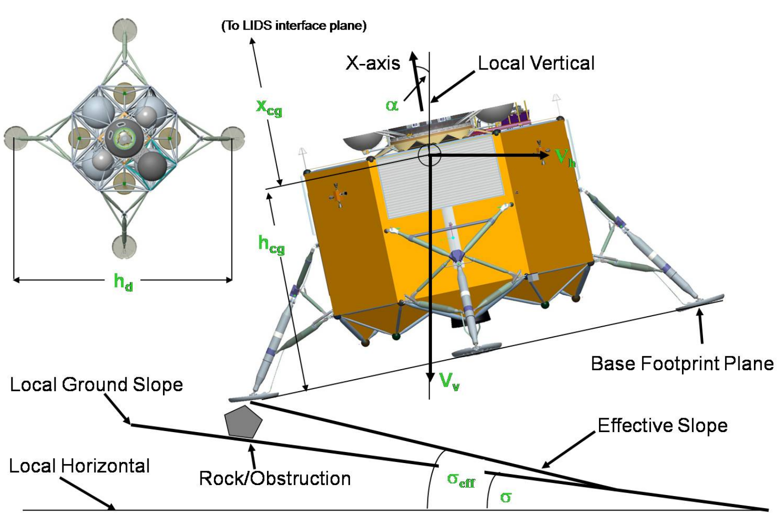

Figure 8. Altair slope considerations.

The current method for locating such a landing site uses remote observation data that have been or are being gathered by orbiting satellites combined with an understanding of likely smaller-scale hazards associated with certain terrain features (eg, craters and their debris fields). Hazards such as the specified 1.4-m rock or crater are features that are generally below the resolution of current or anticipated remote observation data, however. There thus will be some amount of uncertainty about the actual hazards for any landing site that is selected by this method.

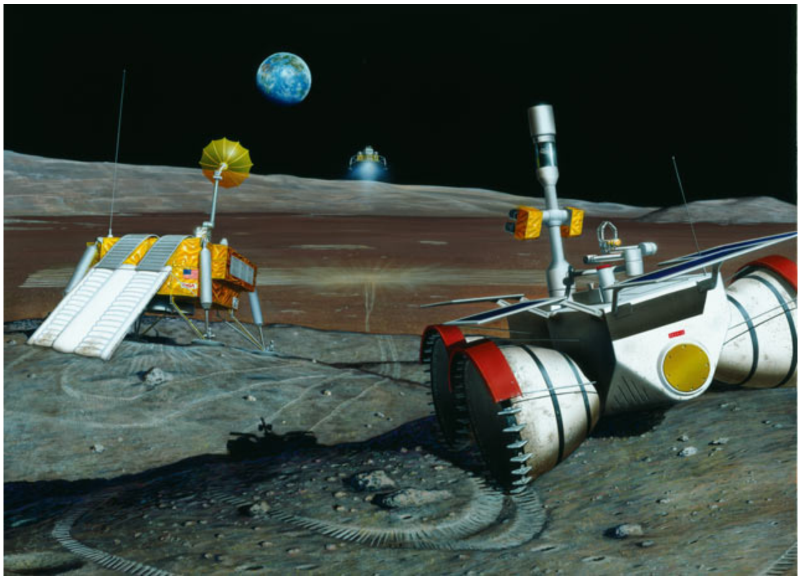

Figure 9. A representative concept for a robotic rover observing the landing of human crew members after surveying their landing site to validate the safetv and viabilitv of the site.

To compensate for this uncertainty regarding actual surface hazards at a landing site, the current lunar lander design incorporates a LIDAR that will acquire a higher-resolution image of the landing site approximately 107 sec (77 sec after pitch up and on final approach, plus 30 sec descending to the touchdown point) before landing. This image will be analyzed by on-board computer algorithms and the crew to make a final determination regarding actual safety of the selected landing site.

In the scenario being simulated in figure 9, robotically driven vehicles will have already arrived at the landing site. This means that there is an opportunity to use the mobility and on-board sensors of these vehicles to assess the selected landing site in greater detail and perhaps validate the safety of this site before the arrival of the lander.

In general, what we are trying to test are approaches to use robotic surface assets to:

- Validate the safety and acceptability of landing site selected using remote observation data
- Mark (visually or with simulated active or passive avionics) the selected landing site

2.2 Methodology overview

The scenario being simulated in these field experiments and the specific hypotheses being tested were detailed in section 1 of this report. The methodology used to carry out these field tests was to simulate only those aspects of the scenario relevant to the six hypotheses. In this regard, we are simulating:

- Terrain using the area surrounding the HMPRS
- Remote observation data of comparable types and resolution to those expected for the scenario that is being simulated
- Sensors representative of the type and resolution of those expected to be operating on surface assets in the scenario that is being simulated
- Earth-based facilities with similar capabilities and distributed in geographically separated locations that are expected to be representative of both the facilities and the operations used in the scenario that is being simulated
- Processes and procedures that have been structured primarily to accomplish the field tests but also to be representative of operations that will be used for this scenario as best as we understand it at this time

The following aspects were not simulated in these field tests due to logistical limitations and the PI's determination of their relatively low importance in accomplishing test objectives:

- Surface asset trafficability
- Real-time communication or command and control of surface assets

We will discuss these aspects in greater detail in the remainder of this section.

2.2.1 Study Distributed Operations

Like aspects of the lunar mission that are being simulated, these field experiments are using assets that are geographically distributed and remote. The relevance of these test locations and facilities and the methods used to tie them together are described in the following subsections.

2.2.1.1 Devon Island

Devon Island, which is located in the Territory of Nunavut in Canada, with its 20-km-diameter and 39-MY [million years]-old Haughton impact crater (fig. 10), was selected as the analog location for this study. The HMP has been conducting NASA-funded planetary analog field investigations in science and exploration at the site since project initiation in 1997 (Lee, P. 1997. A unique Mars/Early Mars analog on Earth: The Haughton impact structure, Devon Island, Canadian Arctic. In *Conf. on Early Mars: Geologic and hydrologic evolution, physical and chemical environments, and the implications for life.* LPI Contrib. No. 916, 50.; Lee, P. 2002. Mars on Earth: The NASA Haughton-Mars Project. *Ad Astra*, May-Jun, 2002.; Lee, P. and G. R. Osinski. 2005. The Haughton-Mars Project: Overview of science investigations at the Haughton impact structure and surrounding terrains, and relevance to planetary studies. *Meteor. Planet. Sci. 40*, 1755-1758). The HMP operates a research station as well as an expedition base camp and adjacent airstrip, all of which are established on the northwestern rim area of Haughton Crater. The HMPRS is operated by the Mars Institute in collaboration with the SETI [Search for Extraterrestrial Intelligence] Institute. The facility is currently the largest privately operated polar research station in the world.

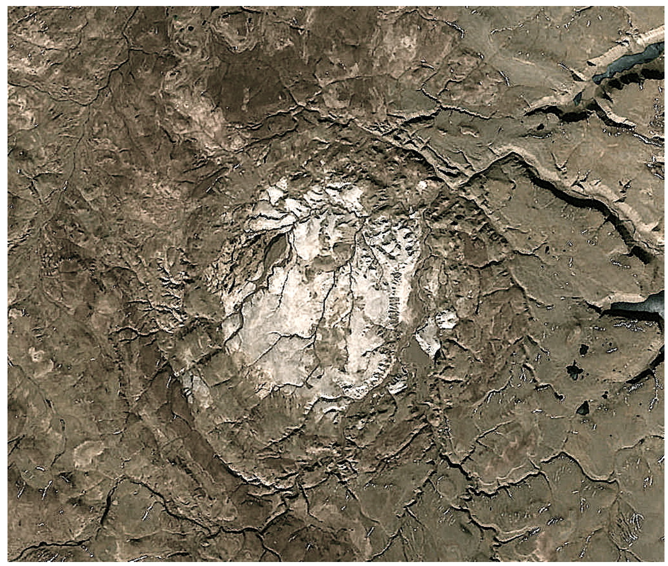

Figure 10. Satellite image of Haughton Crater on Devon Island. This is a 30-km-wide portion of a Landsat 7 scene in near-true color.

Devon Island is the largest uninhabited island on Earth with a surface area of approximately 66 800 km^2. Its geology presents two major provinces: a thick (presently ~1.3 km), almost horizontal sequence of Paleozoic (Cambrian to Devonian) marine sedimentary rocks dominated by carbonates (dolomite and limestone) that form part of the Arctic Platform; and a Precambrian crystalline (gneissic and granitic) basement lying under the stack of marine sediments, forming part of the Canadian Shield. The Paleozoic sediments present a gentle dip of approximately 4 deg towards the west. The flat-topped plateau characterizing much of the surface of Devon Island is an old erosional surface (peneplain) exposing sediments of increasing age towards the east.

The coastal areas of the island present steep sea cliffs and deeply incised glacial trough valleys and fjords, many of which were likely last occupied by ice during the Last Glacial Maximum that ended approximately 10 000 to 8000 years ago. A substantial ice cap representing a remnant of the Laurentide/Inuitian ice sheet system still occupies the easternmost third of the island. The rest of Devon Island presents a barren rocky surface cut by sinuous glacial trough valleys, dendritic meltwater channel networks, and clusters of small lakes.

The Haughton Crater area on Devon Island shows characteristics that make it particularly suitable for the described lunar analog field tests (Table 3).

Table 3. Haughton Crater, Devon Island as a Lunar Analog Site

Haughton: Lunar Science Fidelity Areas		
1	*Impact Crater*	Haughton is an impact structure; it therefore is an example of a class of fundamental and common geologic features on the Moon.
2	*Shackleton Crater Sized*	Haughton is ~20 km in diameter and, therefore, is similar in scale to the 19-km Shackleton Crater on the Moon as well as to many other small- to medium-sized lunar impact structures. Science issues and investigations about Haughton are at spatial scales relevant to Shackleton Crater.
3	*Range of Impact Features*	Haughton presents massive exposures of well-preserved, impact-generated materials (eg, impact melt breccia, shocked rocks), a wide range of impact features (eg, ejecta blocks, megablocks, ejecta blanket remnants), and meter to multi-kilometer-scale impact-produced landforms and structures (eg, central uplift, circular and radial faults, down-faulted terraces) of at least partial relevance to the Moon, both in terms of origin and scale of exposure.
4	*Impact Breccia*	The impact breccia deposits at Haughton represent a one-impact event-generated regolith. While in many ways very different from the lunar regolith (physically, compositionally, regolith maturity-wise, weathering-wise, etc.), the Haughton impact breccia nevertheless presents petrologic and mineralogic features found otherwise only in an impact-generated regolith – particularly in shock-fused angular clasts, shocked polymict rubble, etc.
5	*Impact Excavated Basement*	Target and country rocks at the Haughton site, while very different from lunar materials in composition, nevertheless present a wide compositional and textural variety ranging from carbonates (limestones, dolomites) to granites and gneisses, the latter being derived from impact excavation of the Devon Island crystalline basement. The abundance and distribution of shocked basement rocks at Haughton provides relevant clues to how originally deeper crustal materials on the Moon might have been exposed at the surface by (repeated) impacts.
6	*Subsurface Ice*	The Haughton subsurface is a permafrost rich in ground ice. Ground ice occupies much of the interstitial and pore spaces in Haughton polymict impact breccia in particular. As such, Haughton offers an interesting opportunity to investigate relationships between subsurface volatiles and impact-generated host substrates. While the origin, abundance, and distribution of any water ice in the lunar polar regolith is expected to vary greatly from the situation at Haughton, instruments and approaches to mapping ground ice are related (eg, E/M Sounder).
Haughton: Lunar Operations Fidelity Areas		
1	*No Vegetation*	Because Haughton is set in a polar desert, the landscape at the site is devoid of vegetation, which is a critical for our proposed study. Vegetation cover would be a major problem given that we want to assess the usefulness of robotic scouting for planning lunar exploration.
2	*Terrain*	The terrain at and around Haughton presents a wide range of roughnesses, slopes, and topographic obstacles of broad operational relevance to the Moon. While the steep-walled sinuous valleys dissecting plateau high grounds around Haughton Crater have a very different origin from rilles on the Moon, they provide adequately relevant obstacles from an operational standpoint.
3	*Permanent Daylight*	There is permanent daylight in the summer at Haughton, which is critical for enabling relevant simulations of robotic rover operations on the Moon, both lunar polar operations and lower-latitude operations.
4	*Outpost*	The HMPRS is established in the rim area of Haughton Crater (much like a lunar outpost at Shackleton Crater on the Moon would be) and represents the only infrastructure within an area of several thousand square kilometers. The HMPRS is thus relevant as a lunar analog base from which our pressurized-rover-based science and exploration traverses can be deployed in any direction and out to any relevant range. Note: Pressurized-rover-based traverses as a science concept of operation are independent of an outpost-based architecture.
Lee, P. 2008. Haughton-Mars Project: Analog pressurized rover-based science and exploration studies. Proposal to NASA SMD MMAMA Program (NNH08ZDA001N-MMAMA). 29 pp.		

The HMP site is currently listed as one of several key analog activities in NASA Structures and Mechanics Division (SMD) Announcements of Opportunity for the Moon/Mars Analog Mission Activities (MMAMA) Program. In the first 3 years of its existence (2008-2010), the MMAMA Program selected and funded six research proposals for *lunar* science and exploration at HMP. Table 4 shows the

science traceability matrix associated with MMAMA-funded research led by the ARC IRG at HMP using the IRG K-10 robotic rover. The matrix connects specific science objectives addressed by K-10 at HMP to specific, top-level lunar science and exploration goals outlined in NASA strategic planning documents published by the National Research Council (NRC) and the NASA Advisory Council (NAC). Note that the E/M Sounder was not used during these experiments.

Table 4. Science Program Traceability Matrix

Lunar Science Themes	Lunar Science Goals (NAC + NRC)	K-10 Rover Payload	K-10 Field Test Science Theme and Objective
Lunar Regolith – Structure	NRC: 2a NAC: mGeo-6, 10	Gigapan Microcam LIDAR E/M Sounder	Near-subsurface structure transects at Haughton Crater: • Rim Area Country Rocks to Intracrater Impact Breccia; HMPRS to Drill Hill: 1 x 1 km • Impact Breccia Central; Drill Hill 3 km
Lunar Regolith – Volatiles	NRC: 4a NAC: mGeo-12, 13, 14	Gigapan Microcam LIDAR E/M Sounder	Surveys/mapping of ground ice at Haughton Crater • Plateau and Rim Area Outside Haughton Crater • High Ground Inside Haughton Crater • Low Ground Inside Haughton Crater • Transects Across Valleys Inside Haughton Crater
Lunar Regolith – Mineralogy & Sample Selection	NRC: 1b, 1c, 3a, 3b, 4a NAC: mGEO-2, 4, 5, 6, 7, 8, 11, 16	Gigapan Microcam LIDAR E/M Sounder	Compositional transects across Haughton Crater • Country Rocks and Soils: HMP to Drill Hill, 4 km • Impact Breccia Rocks and Soil: Drill Hill, 1x 1 km • Fluvio-Glavial Deposits: Haughton Crater Rim to Drill Hill, 0.5 km
Lee, P. 2008. Haughton-Mars Project: Analog pressurized rover-based science and exploration studies. Proposal to NASA SMD MMAMA Program (NNH08ZDA001N-MMAMA). 29 pp.			

The Haughton Crater region of Devon Island has been well characterized for analog work, and appropriate (ie, lunar exploration-relevant) types of remote observation data sets were made available for use:

1. Satellite and air photographs (equivalent to ~1 to 2 m/pixel). These images are located on the Google Earth (GE) Website (multispectral data sets) and as individual air photographs (panchromatic hard copies) published by Natural Resources Canada (NRCan).
2. DEM maps (for selected areas) and 10-m contour topographic maps at 1:50,000 scale (hard copies from Energy, Mines, and Resources Canada; digital overlays of these same maps are also compatible with GE).
3. Radar imaging (RADARSAT digital imaging acquired using a single 5.3-GHz C-band SAR [synthetic aperture radar] system at a wavelength of 5.6 cm, yielding a spatial resolution of ~25 m/pixel, provided by Pascal Lee in April 2010)

For the HMP-2010 field season, the Mars Institute provided both logistical and technical field support, particularly to ensure safe living and working conditions on Devon Island; enabled scouting excursions by ATV [all-terrain vehicle] between the HMPRS and the test area; and secured remote communications and networking capabilities, which were procured by contract to Simon Fraser University.

ARC IRG also deployed a K-10 rover field team to Devon Island. The team allowed us to use some of its equipment and temporary infrastructure to conduct our experiments.

Substantial cost savings for all three experiments were made possible by using the HMP existing field infrastructure on Devon Island – in particular the HMPRS base camp facilities, which afford a safe and reasonably comfortable working environment for on-site experiment planning, replanning, communication with remote support teams, and preliminary data analysis.

The HMP established field communications architecture and safety procedures also create a proven safe working environment in the field, which helps make field deployments to the site more cost effective than if an infrastructure had to be established from scratch.

Shared use of a number of field assets and support personnel at HMP between the various research experiments supported at the site (including other investigations supported by NASA and those supported by the Canadian Space Agency) represented a cost-saving advantage for our three experiments as well.

2.2.1.2 NASA Ames Research Center

NASA FFC is a national Air Traffic Control/Air Traffic Management (ATC/ATM) simulation facility dedicated to solving the present and emerging capacity problems of U.S. airports. The two-story facility offers a 360-deg full-scale, real-time simulation of an airport in which controllers, pilots, and airport personnel participate to optimize expansion plans and operating procedures, and to evaluate new technologies. The facility has established a precedent for enabling stakeholders to achieve consensus through a common vision of the future. Its 360-deg and large-field projection capability also make it useful for exploration scenarios, as we demonstrated during the Human Operated Robotic Science Evaluations (HORSE) Project (PI: Brian Glass, NASA ARC); the HORSE Project was part of HMP 2003 in which Stephen Hoffman and Pascal Lee were involved as co-investigators.

The TRPF team (two participants and two study monitors) used the FFC to display multiple images and satellite views at once. Images collected from the field and stored on a server were displayed in the FFC. Voice and/or text links were available to HMP/Devon Island during the time this team was in the FCC. A WebEx and telecom session were also available to the remote participant from ESA.

During the OSP and LSV experiments, operations at ARC were collocated with the K-10 operations team at its home building (ARC, Bldg. 269). The K-10 operations team is able to install the workstations and displays needed to support its remote control of the K-10 rovers in any sufficiently large conference room with a network connection.

2.2.1.3 Tele-participation (Johnson Space Center and European Space Agency/European Space Research and Technology Centre)

Not all of the participants were able to travel for the execution phases of the study. For those who could not travel, telecom and WebEx sessions were created so they could participate.

- TPRF: Tele-participation was used for planning and, with the ESA member, during execution. The additional planned use for additional team members at JSC did not materialize due to a conflict with International Space Station (ISS) support needs and new execution dates.
- LSV: Tele-participation was used between ARC and JSC during the final planning and evaluation of surface imagery. Additional planned use during the execution phase did not occur as the execution phase was canceled due to weather.
- OSP: Tele-participation was not used during execution as the planned remote science team was not able to participate during the revised execution dates.

2.2.2 Remote Observation Data Sets

The remote observation data likely to be available for the Malapert Massif region by the time human exploration is under way will be derived from the LRO or similar sensors. This data set is characterized as:

1. Imagery (Lunar Reconnaissance Orbiter Camera [LROC])
   a. Wide Angle Camera (WAC)
      1) 100 m/pixel (monochrome)
      2) 100 to 400 m/pixel (seven-color)
   b. Narrow Angle Camera (NAC):
      1) 0.5 m/pixel at 50-km altitude
      2) 1 m/pixel (polar mosaics down to 85.5 deg latitude)
      3) 2 to 10 m/pixel (geometric or photometric stereo topography)
2. Topography (Lunar Orbiter Laser Altimeter [LOLA])
   a. Individual spots: ±1 m vertical, ±50 m horizontal
   b. Data from laser ground tracks process into the equivalent of approximately 25-m contour topographic maps or DEM maps
      1) Polar: complete coverage
      2) 45 deg latitude: approximately 200 m separation between ground tracks
      3) Equator: approximately 1 km separation between ground tracks
3. Radar (Mini-RF [radio frequency] radar – side-looking)
   a. Two modes: “wide” mode with 75 m/pixel and “zoom” mode with 30 m/pixel
   b. Because this is side-looking, there will be a “hole at the pole” for radar data: Malapert Massif will be visible; Shackleton Crater will not be visible

The northwest part of Haughton Crater and extending out from the crater to almost 15 km (~290 km^2) has been imaged at a resolution similar to that expected from LRO.

Table 5. Google High-resolution Area on Devon Island

Corner	Latitude (deg)	Longitude (deg)
Southwest	75.360272	-90.137386
Northwest	75.511041	-90.128638
Northeast	75.508942	-89.517271
Southeast	75.358091	-89.526965

1. Satellite and air photographs (equivalent to ~1 to 2 m/pixel). These satellite images used were in GE. A significant area around the crater and HMPRS has been imaged at this higher resolution (Table 5**Error! Reference source not found.**). The air photographs were 23-cm×23cm-hard copies ordered from NRCan; A16747-19 to 23, A16752-37 to 41, and A16752-179 to 182.
2. Topographic Maps (10-m elevation contour) and DEM Maps (selected areas). The topographic maps were NRCan maps obtained through www.gpsvisualizer.com using the GPSVisualizer_overlays.kml interface, downloaded from the site. The DEM maps used were those already in GE.
3. Satellite radar imaging acquired by RADARSAT at a 5.6-cm wavelength, at a spatial resolution of ~25 m/pixel.

2.2.3 Terrain Zone Classification System

The analog community believes, based on previous field tests of the Lunar Electric Rover (LER), that a general and consistent way to classify terrain would probably be useful for both planning and re-planning activities related to surface activities such as traverses and landings. As a first cut at such a categorization, Michael Gernhardt and Andrew Abercromby, PIs for many of the recent LER field tests, proposed a set of four zones based on slope, rock coverage, and soil mechanics. The definitions in Table 6 were agreed to for the 2010 Analogs season, and several experiment teams will evaluate the value of such a system and of these definitions in particular.

Table 6. Definition of Trafficability Categories

	Zone 1	Zone 2	Zone 3	Zone 4
Maximum Slopes (deg)	0-5	>5	>15	>20
% coverage medium rocks (15.24 to 30.48 cm)	< 1%	1% to 10%	10% to 40%	> 40%
% coverage large rocks (0.3 to 0.61 m)	< 1%	1% to 5%	5% to 20%	> 20%
% coverage very large rocks (> 0.61 m)	< 1%	1% to 5%	5% to 15%	> 15%
Soil mechanics	Firm	-	Soft	Very soft

The evaluation is performed from highest zone number to the lowest zone number; the first zone that is matched by one of the criteria is the overall zone rating. For example, an area with a 10-deg slope, with no rocks and firm ground, would be classified as Zone 2; since it has a slope between 5 and 15 deg (Zone 2), the area is covered by less than 1% rocks in each category (all Zone 1) and has firm soil (Zone 1).

The TRPF and LSV experiments in this study made use of this categorization scheme, and the results will be presented as part of the analyses of those experiments. The OSP experiment did not require use of this categorization.

2.2.4 Experimental Facilities and Resources

A number of pieces of equipment were used as analogs for what would be available on the lunar surface as well as for support equipment and software tools used in this set of field experiments. We give a short description of these items and how they were used in the following subsections.

2.2.4.1 Surface vehicles and sensors

Figure 11. Device used to measure local slopes at each data collection station of the field tests. The device consisted of a 1-m-long steel pole and a digital angle meter (a small device mounted at the middle of the pole; described in Appendix A).

The vehicles and sensors used as the analog to what might be on a traverse on the lunar surface are detailed in Appendix A.

Only the acquisition of surface imagery and ground truth information were of importance for the TRPF field experiment; there thus was no need for a direct analog to the scout vehicle while obtaining the information. The PI used a Kawasaki Bayou (four-wheeled, one-person ATV) and a Kawasaki Mule (four-wheeled, two-person utility vehicle) provided by HMP to transport the equipment (Iridium OpenPort terminal) and when obtaining required surface-level information. The primary "sensor" used for this effort was a standard digital camera mounted on a pole such that all photographs were taken at the same local height, a digital angle meter was attached to a 1-m staff to determine local slopes (fig. 11), and a handheld Global Positioning System (GPS) set was used to record position every 30 sec.

The initial acquisition of surface imagery and the ground truth information were obtained for the LSV and OSP experiments in the same manner as for the TRPF experiment. For the real-time interaction part of these two experiments, an analog vehicle with additional sensors was required. In taking advantage of the presence of the K-10 team at Devon Island, the K-10 suite of sensors (PanCam – a Gigapan with digital camera; LIDAR; and microscopic imager – close-up digital camera) was used to represent what may be available on a scout. The analog for the scout itself was a HMMWV or Humvee. The Humvee is a modified M997 military Maxi-Ambulance with a tall, habitable rear cab. The K-10 robot with its sensors was fastened to the roof of the Humvee (fig. 6, section 1.5). So in contrast to the initial surface imagery, which was taken from a height of somewhat fewer than 2 m, the Humvee /K-10 mount sensors were about 3 m off the ground. The Humvee was controlled by voice instruction rather than robotically.

For all three experiments, the digital images and GPS information were downloaded to a laptop so that the photographs could be geo-tagged before being transmitted from Devon Island.

2.2.4.2 Iridium OpenPort communication system

The limited bandwidth available during the day (while K-10 team members were independently executing their experiment) and the distance of a large section of traverse route from the HMPRS base camp meant that a remote data terminal would significantly improve the support of the real-time part of the traverse. It is also becoming clear within the analog field test community that additional data transmission paths would be useful for remote locations. Thus, for the experiment, the PI decided to set up an Iridium OpenPort terminal about 6 km from the HMPRS base camp on a hill, near location D0N29 (fig. 5, section 1.5), named Constellation Hill by the local field team.

Unfortunately, due to weather conditions during the real-time part of the experiment, the OpenPort terminal was not used. The terminal would have functioned, but the weather was determined to be unsafe for operations that far from the HMPRS base camp.

However, the PI was able to set up and test the terminal before bad weather set in and found that the system was:

- easy to set up and tear down by one person; and
- able to transmit large (5-MB) imagery without drop-out issues (a potential problem identified prior to deployment).

Additional generic link performance data to characterize the OpenPort terminal operations were gathered and made available to the NASA custodian of the system.

2.2.4.3 Software tools

The planning and field documentation of the route was made easier by assembling several available software tools with which to manipulate GPS data and photographs and create several Excel spreadsheets that included Visual Basic for Applications (VBA) macros. Many of these tools were conceptualized and evolved as the planning and field-test phases of these experiments proceeded. These tools proved to be very useful during both the planning and the field test phases, improving the efficiency of the planning and the field test teams; without these tools, many of the results presented in this report may not have been possible given the limited time and personnel available for these tests. We are documenting the capabilities of these software tools here to illustrate how we were able to improve the efficiencies of our teams. We hope that future experiment teams will also take advantage of these readily available capabilities.

All three experiments made use of the GE local client for document waypoints for the traverse (TRPF), objects to be observed (OSP), and coordinates of the landing area and corresponding hazards (LSV). The coordinate documentation mentioned above was exchanged and communicated by transferring keyhole markup language (KML) files between participants.

The GE local client version was selected instead of the Web-based one as there was a desire to use GE while on Devon Island. The GE local client has the ability to cache a large amount of data and make these data available even when no network connection is available. The cache allowed was sufficient to hold the entire area of interest on Devon Island.

The PI's support team created four Excel spreadsheets that are able to read and manipulate the KML files (based on extensible markup language [XML]) and that were able to directly manipulate the GE client (using the GE component object model [COM] application programming interface [API]). These four spreadsheets perform as follows:

1. Read in a KML traverse route and write out a new KML traverse route that adds parallel lines to display the visual equivalent of a street that is 10 m wide (ie, ±5 m – a distance that was chosen by the planning team; any value could be used depending on circumstances). We allowed that anyone remotely piloting a rover would be allowed free access to maneuver around any single obstacle as long as he or she remained inside this virtual street.
2. Read in a KML traverse route and create a form that includes the coordinates of each waypoint and the bearing and distance to the next way point. These forms were created to make it easier to determine the proper bearing to take for the photograph along the traverse route as well as for areas of the candidate landing sites.
3. Read in a KML traverse route and then use the GE local client to look up the altitude of the way points along the traverse. GE KML files do not have altitude data, so this work-around using the GE COM API was created to get the altitude data. These altitude data were then used to determine slopes (on the of trafficability metrics) along the traverse route.
4. Read in a KML traverse route and create a new KML traverse route with a GE tour of the route. When it is loaded into GE, the new KML effectively creates a "movie" that simulates the view when driving the route with a viewpoint about 2 m (a value that was chosen by the planning team; any altitude could be used depending on circumstances) above the local surface.

In addition to map information and satellite images that are already in GE, we also attempted to overlay other data sources. The Website GPSVisualizer.com has a KML download that uses the GE network link function to overlay additional maps from various other sources. One of these sources was the NRCan Website, which has 10-m elevation resolution topographic maps of Devon Island. We overlaid these maps using the GPSVisualizer KML. We also used the information gained to download the maps for off-line use. We found that combining topographic data with imagery data was very helpful in visualizing the local terrain and, thus, in planning a route that achieved our objectives.

Another software tool that was used extensively was GPSBabel. This piece of software can convert GPS data among several formats (eg, KML, Garmin, and EXIF) and devices. GPSBabel was used to read out data from the handheld Garmin GPS device that was used on Devon Island to record the route traveled when photographs were taken. By coordinating the time of the photograph recorded in the digital image and the time recorded by the handheld Garmin GPS, it was possible to tag those photographs with GPS coordinates. It was then further possible to create a KML file for GE that showed the location of each photograph, and to compare this location with the desired location selected by the planning team.

With GPSBabel and the cached GE data, it was possible to directly tie to a laptop computer in the field the handheld Garmin GPS device. So, in addition to displaying the planned traverse route, the field team would also be continuously shown their current location in GE relative to the planned route.

The Excel spreadsheets and batch files for driving GPSBabel are available from the PI.

2.2.5 Methodology Limitations

No attempt is being made to simulate the trafficability characteristics of a particular mobility system in any of these experiments; these experiments are intended to be independent of the platform carrying the

sensors except for specific characteristics important to the experiment (eg, sensor height above the ground for OSP and LSV experiments, and maximum ground speed of an LER for the OSP experiment). A common focus in all of these experiments is the assessment of the sufficiency of remote observation data sets and the added value of imagery (and, in some cases, additional data types) obtained from a source located on the surface of the planetary body being explored.

For the TRPF experiment, gathering a limited number of surface-level still images is not anticipated to be the method by which navigation decisions will be made for robotic vehicles on the planetary surfaces on which we expect video to be used. Still imagery was used for this experiment due to the limited bandwidth available from Devon Island for the experiments.

A systematic registration error exists in the GE data layers compared to actual geographical coordinates as determined by GPS. This error becomes increasingly large with higher latitudes on Earth. On Devon Island, the offset is on the order of 15 m. We took several measurements of the offset between the position of specific features visible in the GE images and their actual position as determined using a Garmin GPS. The offset and its magnitude were confirmed. HMP confirmed this is a known problem, and the ARC IRG team is working with Google to correct the GE data. For purposes of these experiments, we qualitatively took account of this problem in real time. Given the size of the error compared to normal GPS drift, we decided this was sufficient for the first attempt at these experiments. For future experiments on Devon Island, we suggest registering the GE data again as the K-10 team has done, or converting the actual GPS coordinates to the GE coordinate system.

The handheld Garmin GPS that was used had the nominal expected GPS accuracy. Differential GPS was not used.

An attempt was made to scan and register the NRCan air photographs and integrate/overlay them with other map information in GE. While we were able to get a rough agreement over smaller areas, it was not possible to register the entire image. Additional mapping transformation software is required. As a result, the air photographs were primarily used in the region in which there was no higher-resolution imagery available (ie, from the middle of Section E-F on the planned traverse route to the end of the route at Way Point H) for the TRPF experiment.

2.3 Traverse route planning and following experiment

This experiment was executed in four parts:

1. Definition of the analog traverse by the PI, the available remote observation datasets, and other constraints for planning the traverse
2. Selection of a traverse route and required ground observations by a route planning team (six people)
3. Gathering of the ground observations on Devon Island
4. Simulation of the planned traverse using the data gathered on Devon Island and any real-time data requests

2.3.1 The Four Parts

2.3.1.1 Part 1

The PI established a start point and an endpoint for the simulated traverse; these two points are separated by a straight-line distance of just over 17 km (11 miles; ~15% of the straight-line distance between Shackleton Crater and Malapert Massif). This was deemed (by the PI) to be a reasonable fraction of the total traverse being simulated, and likely to cover a variety of terrain types in the simulation area. Eight way points were inserted between the start point and endpoint of the simulated traverse. These way points are meant to simulate points of interest between the start point and endpoint that could have been introduced for science reasons or operations reasons; eg, a high point in which solar illumination was available. But, the process by which these way points would have been selected was not part of the simulation and there-

fore will not be further discussed. (Note: There is also a practical reason for including these way points; ie, to provide a prominent landmark for the person on the ground to find independent of latitude/longitude should there be any issue with map/image ties with the remote observation data sets being used.) The straight-line distance between all eight of these way points (Table 7) is 22.7 km.

Table 7. TRPF PI-selected Way Points

Way Point	Latitude (deg)	Longitude (deg)	Altitude (m)	Distance to Next Way Point (m)	Total Distance (m)
A	75.447388	-89.904466	267	2743	0
B	75.429575	-89.836597	239	1972	2743
C	75.417903	-89.889642	235	2816	4715
D	75.415621	-89.989798	270	5752	7531
E	75.366578	-90.054889	256	2731	13283
F	75.350297	-90.127619	287	3777	16014
G	75.348039	-90.261600	280	2963	19791
H	75.321626	-90.275253	309	N/A	22754

The following datasets were selected by the PI for use by the planning team:

1. Satellite and air photographs (equivalent to ~1 to 2 m/pixel); these images are located on the GE Website, which includes DEM information and individual air photographs
2. Topographic maps (10-m elevation contour) and DEM maps (selected areas)
3. Satellite radar imaging (25 m/pixel resolution)

The following ground rules for vehicle restrictions were adopted for this analog:

1. Route restricted to slopes of less than 15 deg (Note: This slope is representative of the upper limit that can be negotiated by the vehicles in the hypothetical convoy)
2. Objects of a height greater than 61 cm cannot be cleared (Note: This height is representative of the lowest clearance of the vehicles in the hypothetical convoy; an object of roughly this size cannot be detected directly using the image resolution available)

2.3.1.2 Part 2

The traverse path and photographs to be taken were done in a four-step process.

Step 1: Using material (ie, remote observation data) provided to the planning team, team members were asked to determine the shortest route that could be traversed by all elements of the convoy. If the planning team was fairly sure, but not completely convinced, that the particular route was feasible, team members were asked to prepare a possible alternate route to bypass the questionable area. The planning team documented the routing as a set of additional way points between those selected by the PI. The group was also asked to assign a trafficability rating to the selected route using the categories defined in Table 6.

Step 2: With the traverse path determined, the planning team was asked to decide which ground-level photographs along the primary route are needed to confirm that the path picked is passable. The planning team was advised to take into account turns, possibly hidden depressions, and rocky terrain in determining the ground-level photographs needed. The planning team was told that a standard digital camera (see section 4.1.5) would be used with a default field of view (FOV) of 40 deg (horizontal) × 30 deg (vertical) and that team members could request panoramic views, effectively creating FOVs of approximately 80, 120, … × 30 deg. The group documented these photograph requests as a set of locations (latitude, longitude), bearing, and FOV size for each photograph.

Step 3: The team was asked to revisit the path selected and determine whether there are locations in which use of a point of perspective would be useful (eg, to check an alternate route or to provide a view not from the traverse path). Again, the team was asked to document these photograph requests as a set of locations (latitude, longitude), bearing, and FOV size for each photograph.

Step 4: This was not as much a planned step as an immediate lesson learned, in that the planning team actually iterated through the above process three times. This will be discussed later in the analysis.

2.3.1.3 Part 3

The third part of the experiment consisted of the PI traveling the route laid out by the planning team to gather the requested photographs and document the ground truth. The PI obtained the photographs, tagged them with GPS coordinates, and transmitted them from the HMPRS base camp using the NASA NOMAD Large File Transfer tool. The PI also noted and documented ground truth data regarding the characteristics of the terrain along the planned route, in particular whether the planned was "safe" for all vehicles to follow either due to rocks or slope as well as the trafficability (Table 6) of the route.

When the PI believed the route was unsafe for the convoy or thought the traverse team may perceive a problem, the PI took additional photographs that might help the groups resolve the situation. These additional photographs were only taken as a timesaving measure, anticipating the team would request such a photograph during the execution phase. During the execution phase, the traverse team would only be allowed to view the photographs if the team members requested a photograph that matched one of the photographs the PI took.

2.3.1.4 Part 4

The final part of the experiment was to "execute" the traverse. The images and GE view along the planned route on Devon Island were presented to the traverse teams on displays in the FFC; the primary image was also shown on WebEx for remote team member(s). The images were displayed no faster than the nominal ground-ruled speed of the traverse; ie, 5 km/h, which is 72 seconds per image for images 100 m apart. For each image displayed, the traverse team decided and recorded whether the route was passable for the segment represented by the image and determined the terrain trafficability category (Table 6). Since slope is part of the trafficability category, the traverse team was also provided with the ground-truth slope at the position of the photograph.

At locations at which the planning team had previously determined an alternate route might be needed, the traverse team was presented images of both the primary and the alternate route from that location. The traverse team then determined whether the two images provided sufficient information to select one route over the other. In cases in which there was no clear advantage of one route over the other route, the traverse team was instructed to continue on the primary route.

When the team came across a section of route that they determined was impassable, two scenarios could come into play depending on the situation:

- If team members had already determined that they section may be a problem, the team would have already planned an alternate route. In this case, the team would back up to the start of the alternate route and proceed on that alternate route.
- If there was no alternate route or all alternate routes had been exhausted, the team members were asked to plan an alternate route "on the fly." Originally, the plan had been to allow the traverse team to request additional imagery at the "current" traverse location. The PI on Devon Island would have taken this additional imagery in real time and sent it back over the OpenPort terminal. However, the weather conditions at Devon Island did not allow for this scenario. Instead, the test director in the FFC used the ground-truth notes and some additional imagery the PI had already taken to make rulings on the alternate routes the traverse team proposed.

The time spent evaluating and discussing each imagery location and the discussions concerning alternate routes were recorded by the test director.

There was sufficient time during this execution phase of the experiment to allow the traverse team to go back and execute all of the alternate routes that had not been selected during the initial traverse.

Note: The procedure described above differs from that in the original proposal in that during the planning phase, it became obvious that given the available bandwidth for data transfer from Devon Island and the characteristics of the terrain involving two scouts in front was not a viable option. Also, due to a change in the schedule and a problem that developed on the ISS during this period, several members of the original traverse planning team were unable to take part in the traverse execution phase.

2.3.2 Traverse Route Planning and Following Hypothesis 1

TRPF-H1: The available remote observation data sets of a region to be traversed are sufficient for planning primary and alternate routes for the traverse.

Testing this hypothesis will help inform NASA on whether the expected available remote observation data will be sufficient to plan robotic traverses across the Moon, more detailed remote observation data are needed, or a longer period of time should be allowed to complete the traverse. This information will, in turn, help NASA decide on the need for precursor missions sufficiently in advance of crewed missions to be of use.

2.3.3 Traverse Route Planning and Following Hypothesis 2

TRPF-H2: Robotically implemented traverse route execution will require surface-level imagery to identify and maneuver around local hazards/obstacles.

Testing this hypothesis will help inform NASA on whether there is a need to develop robotic scouts and, if so, help NASA start to determine the number of scouts that may be needed. As the remote observation data are of a lower resolution than the size of some of the hazards that may hinder the progress of a traverse, there is an expectation that obstacles will be encountered at some marginal number of locations. The results will help to start formulating an opinion on the capability needs for a scout in quality of information returned.

2.3.4 Traverse Route Planning and Following Hypothesis 3

TRPF-H3: Route-traversing efficiency will improve in direct proportion to the number of surface-level imagery sources used to support a traverse.

After the experimental protocol was approved, we ran into problems implementing the plan to test this hypothesis. The original plan was to take two (or more) set of images along each of the planned routes. The multiple sets of images would have all been along the line of traverse travel, but offset to the side by 200 m. Two problems developed with this plan: One, the amount of data that would have been needed for multiple sets of data ended up being more than our communication allocation would allow. Two, there were several sections of the selected routes where such an offset would not have been possible due to being on a crater rim or in a valley that was too narrow for the offset.

As a result, no data were explicitly gathered to test this hypothesis. As it turns out, the selection of primary and alternate routes provided the team an opportunity to qualitatively address this question and gather information that should help our team members develop a more refined experiment to test this hypothesis in future.

2.3.5 Traverse Route Planning and Following Data to be Gathered

Several metrics were gathered concerning the planning of the traverse route, the route itself, and the simulation of the traverse to test the hypotheses described above. In addition to general PI, test director, and team notes, 10 specific metrics (Table 8) were gathered as part of the experiment.

Table 8. TRPF Metrics List

ID	Description
TRPF-D1	Nominal route length compared to straight-line distance between way points
TRPF-D2	Maximum route length (ie, all worst-case alternate routes) compared to straight-line distance between way points
TRPF-D3	Number of alternate routes required as determined by the route planning team during the planning phase
TRPF-D4	Net speed across the entire route (Note: "Net speed" in this usage will be associated with the time required by the route panning team to make decisions at key points along the traverse route; this will be independent of the vehicle used for scouting)
TRPF-D5	Time required to assess, decide, and issue command on unplanned anomalies
TRPF-D6	Number of alternate routes used
TRPF-D7	Number of unplanned anomalies encountered
TRPF-D8	Ground-truth notes and assessment (eg, zone classifications) of the straight-line route between way points and the planned traverse route
TRPF-D9	Number of changed Zone classification due to improved understanding provided by surface-level imagery
TRPF-D10	Time required to assess, decide, issue command, and execute traverse down the alternate route

Metrics TRPF-D1 through -D3 were gathered during the planning phase, while the rest of the metrics were gathered during the execution phase of the experiment.

TRPF-D6 and -D7 are required to evaluate TRPF-H1, and TRPF-D6 through -D8 are required to evaluate TRPF-H2. The rest of the metrics are being gathered to allow a more general discussion of the execution of the experiment, since this is the first attempt at these experiments, to determine which data may be useful in testing hypotheses in future experiments.

2.4 Opportunistic science protocol experiment

Long-range planetary surface traverses, such as the Shackleton Crater to Malapert Massif robotic traverse on the Moon, will offer opportunities for a limited amount of scientific investigations to occur during the traverse. In the case of the Shackleton Crater to Malapert Massif traverse, while the primary objective of the traverse is to get the assets in place at Malapert Massif within the time allotted, if the traverse is proceeding on or ahead of schedule, time will be available to pause at points of scientific interest; and that time may be used to conduct opportunistic scientific investigations. These points of interest may be identified during the process of reviewing remote observation data as the traverse is being planned, or encountered at unexpected locations along the traverse. For either case, a protocol is desirable that can be used by the science community and traverse planners to structure this "opportunistic" science investigation in such a way that the amount of time available to pause for this investigation can be compared to the amount of time likely to be needed for an adequate investigation. The entire set of robotic assets pauses in the traverse for this investigation in some approaches; but other approaches have been suggested in which only some of the robotic assets participate in the investigation while the rest of the assets continue on. This OSP experiment provides data that are useful to either approach, and may even be relevant to crewed traverses in addition to the robotic ones being investigated.

This experiment postulated a three-step protocol to conduct an opportunistic science investigation; the time required to complete the basic steps (defined below) of this protocol are directly proportional to the scale of the object being investigated. It should be noted that while (i) a number of factors other than target size will likely also affect the time required to investigate a science target of opportunity (eg, the inherent complexity, uniqueness, geologic context, etc. of the target), (ii) the investigation time of a target may increase with its size but not necessarily in direct proportion to the target. Therefore, the above postulate is merely intended to serve as a starting point. Departures from this initial postulate are expected to become evident as part of the practical outcome of the OSP experiment, and analyzing the cause(s) of these departures will be revealing.

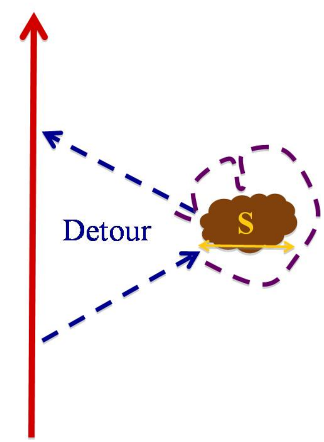

Figure 12. The OSP experiment. The red line represents the original traverse path. The blue and purple dotted lines represent the detour to inspect the object.

Figure 12 illustrates the basic features that must be accounted for in estimating the time needed for this opportunistic investigation. The red arrow indicates the nominal traverse path. The dark blue arrows indicate the path to the object and returning to the traverse path. The time for this "detour" can be calculated based on the average speed of the robot(s) conducting the investigation; no data on this part of an opportunistic science investigation will be gathered during this experiment. The time needed to investigate this object, indicated by the purple line surrounding the object, is determined by the three-step protocol. This three-step protocol is defined as follows:

1. General reconnaissance of all sides of, or circumnavigating the entire boundary of, the object being investigated. Data from this reconnaissance include, at a minimum, imagery plus other TBD data sets (for this experiment, LIDAR and a microscopic imager be will included).
2. Decide whether the reconnaissance data are sufficient to develop a general characterization of the object being investigated, and identify any portion of the object requiring further detailed investigation (including a result of "no additional investigation required").
3. Develop a plan to explore each additional detailed investigation and/or sampling and carry out those investigations (type[s] of data to be collected, positioning of the sensors to gather these data, etc.).

Step 3 in this protocol could be repeated many times for one or more of the detailed areas of the object being investigated. The total time required to complete characterization of the target to the satisfaction of the science team would be recorded as the time needed to execute the protocol.

This experiment leveraged the equipment and operations set up in support of the NASA SMD MMAMA program-funded ARC IRG K-10 experiment on Devon Island during the HMP-2010 field campaign, including the K-10 science team. The experiment also used a small human-rated pressurized rover analog on Devon consisting of an HMP Humvee with the K-10 robot mounted on its roof (see section 4.1).

The objects investigated were chosen in advance by the PI in one (Site A, fig. 13) of the three areas previously selected by the K-10 science team on Devon Island. Use of an area selected by the K-10 team allows this experiment to leverage a wireless network set up to support the K-10 team. To test the hypothesis, two objects in each of five different size ranges (ie, 10 total objects) will be selected in these areas. The five size ranges will be 0.5, 2.5, 5, 25 m, and 50+ m. For example, a rock whose largest dimension is approximately 5 m could be a candidate object; or a debris field with a diameter of approximately 50 m could be a candidate object.

The SPR analog was positioned in close proximity to the candidate object for each of the 10 candidate objects (ie, close enough for the entire candidate object to be seen in a single 40-deg FOV image). The science team was given the coordinates of this object (so team members can observe its location relative to the general area of study) and shown the single 40-deg FOV image. From this initial information, the

team decided first whether the object warranted further investigation, and then decided on an initial observation plan for the object. Using this observation plan, the team then provided voice commands to the SPR driver and K-10 sensor operator to obtain the observations. The science team evaluated the observations as they came in and decided whether modifications to the observation plan were needed. If so, the changes were again communicated by voice. The test director, who was collocated with the science team, recorded an annotated time log that started when the science team was shown the initial image and ended when the science team decided to move to the next object. Science team members were also asked to keep a log of their science decisions as to which instruments to use, and to document their findings for each object. This process was repeated for each new object until time expired for the experiment.

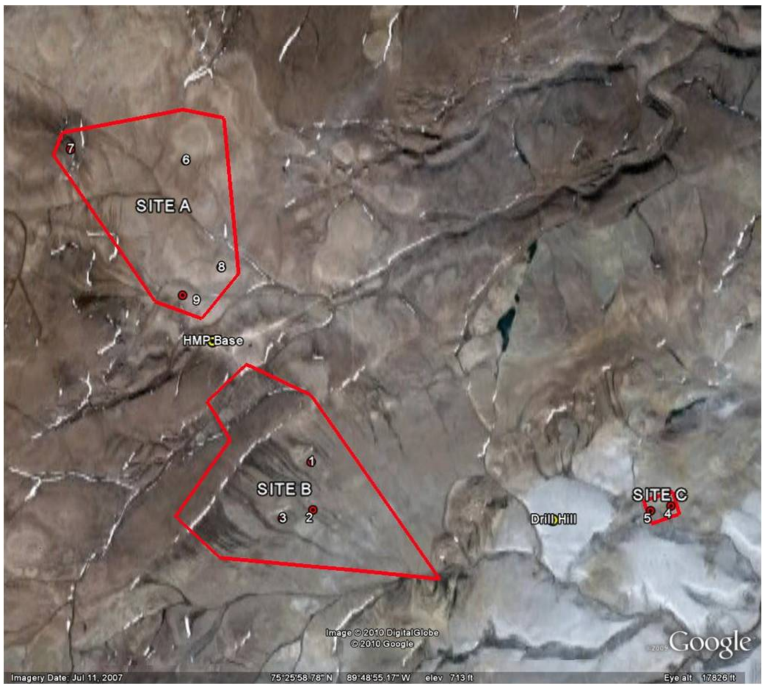

Figure 13. K10 investigation areas. Site A, in the northwestern rim area of Haughton Crater, was used to select candidate science targets of opportunity for the OSP experiment. The scene is approximately 9 km across. The Haughton rim is marked in this scene by the linear-faulted zone crossing diagonally from lower left to the upper right.

2.4.1 Opportunistic Science Protocol Hypothesis 1

OSP-H1: The amount of time needed to investigate the scientific characteristics of a target of opportunity is in direct proportion to the size of the target.

Knowing how long it takes to execute an observation program for target features of various sizes will allow NASA mission planners to have a basis on which to predict the potential impact that investigating science targets of opportunity might have on mission operations – in particular on mission timelines. Conversely, it will also help mission planners allocate sufficient time and resources for opportunistic science activities during traverses that could accommodate such activities.

As regards the OSP experiment, it is recognized that size scale is likely only one of several factors determining the time needed to investigate a geologic feature or any surface science target in general. The aim of the OSP experiment is therefore not to achieve a rigid mathematical relation between target size and required investigation time, but to begin examining systematically and as quantitatively as possible the key factors that influence implementation of science operations in planetary surface exploration activities; to understand the possible variance associated with these factors; and to provide guidelines that can be used to make quantitative estimates of the time and resources needed to carry out one of these opportunistic investigations.

2.4.2 Opportunistic Science Protocol Data to be Gathered

To test the hypothesis described above, several metrics were gathered during execution of the experiment. In addition to general PI, test director, and science team notes, four specific metrics (Table 9) were gathered as part of the experiment.

Hypothesis OPS-H1 will be considered true if the following is true:

- There is a function with a least-squares curve-fit correlation coefficient greater than 0.90 between OSP-D1 and the sum of OSP-D2 to -D4.

Table 9. OSP Data Items

ID	Description
OSP-D1	Measurement of size of object of interest to science.
OSP-D2	Time needed to perform initial evaluation.
OSP-D3	Time needed to decide if close-up additional data is needed.
OSP-D4	Time needed to execute additional data.

2.5 Landing site validation experiment

The current Altair ConOps calls for this vehicle to land within 100 m of a specified location on the lunar surface. On approach to this landing site, the Altair lander will pitch over from a horizontal configuration to a vertical configuration 107 sec prior to landing. At this time, the Altair lander will be approximately 1000 m away from the landing site at approximately 15 deg elevation (fig. 14). An LIDAR instrument on board the lander will acquire an image of an area measuring 180 m × 180 m immediately surrounding the landing site (fig. 15). The crew will use a combination of visual cues out the Altair lander windows and the LIDAR image to determine whether to land at the nominal site or to divert to a different site.

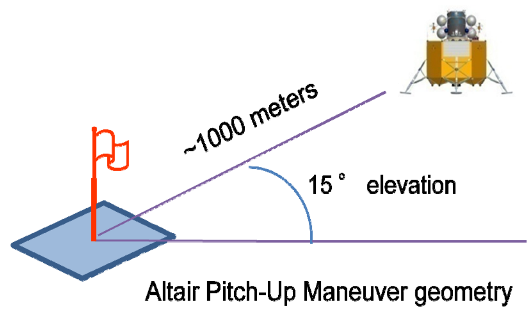

Figure 14. Altair approach to landing site.

To account for the nominal landing and possible divert landing sites, hazards must be identified within the central 180 m × 180 m square plus the eight squares surrounding it , a total area of approximately 500 m × 500 m (fig. 16).

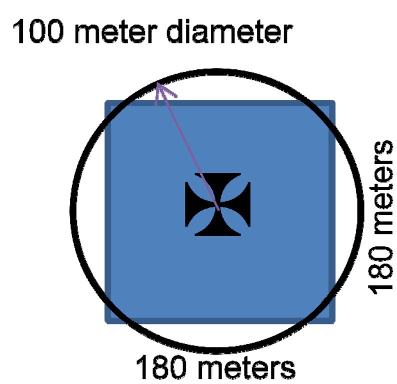

Figure 15. Landing site target geometry.

A landing site would be considered “safe” if the central square plus at least one of the eight surrounding squares (a “divert” site) is free from apparent hazards (excessive slopes, protrusions, or depressions as described in section 2.1.2). A “safe” landing site would be considered validated if all hazards identified from remote observation data are confirmed by robotic assets and no additional hazards are identified in any of the nine squares that are initially considered “hazard free.”

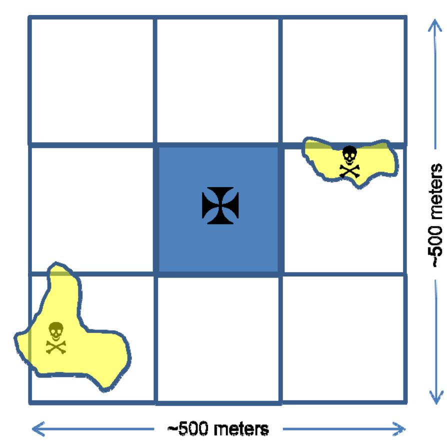

Figure 16. Safe landing site.

This experiment was carried out in two phases:

1. Selection of a “safe” landing site for the Altair lander consistent with the current Altair ConOps using remote observation data (section 2.2.1.1). As part of this selection, all hazards within a 500-m square surrounding the selected landing site (further details provided below) were identified.

2. Gather ground-truth data at the selected landing site. A portion of these data will be gathered using a simulated robotic scout. Using these data, validate that the selected landing site is a "safe" place for the Altair to land. In addition, provide visual markers at a selected point near the landing site to aid the crew during landing.

This simulation began with the landing site selection team being provided with a latitude and longitude as the designated location of "Malapert Massif." The team was asked to identify a candidate landing site that meets the previous definition of a "safe" landing site (the approximately 500-m × 500-m area depicted in fig. 16) located within a 1.0-km radius of Malapert Massif analog. (This 1.0-km-radius circle is a ground rule selected by the PI for two reasons: (1) to constrain the area that the landing site selection team needed to examine, thus preventing this team from spending an inordinate amount of time trying to find the "perfect" landing site; and (2) to keep the selected landing site within the wireless communication range of the HMPRS base camp, which will be a factor in the second phase of this experiment.) Once the landing site was selected, the team identified the location and characterized the hazards within each of the nine squares. The terrain characteristics previously defined in Table 6 were used to describe the characteristics of these identified hazards. Data collected during this phase include:

- The latitude and longitude of the center of the landing site and the orientation of the 500-m × 500-m square surrounding this point.
- The location of any hazard (the latitude and longitude of the approximate center of the hazard), the boundaries of the hazard, and the type of hazard (fig. 17) within each of the nine squares.
- The landing site selection team also provided a description of a route that the Devon Island ground team could use to investigate documented hazards. This was done as a backup in case of communications problems during the real-time part of the experiment.

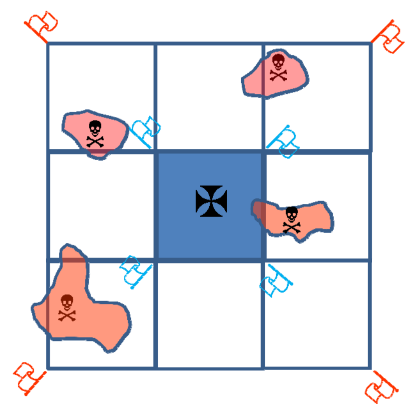

Figure 17. Target landing site with hazards. The flags indicate the locations for the initial photographs taken by the scout.

The above information was initially documented on hard copies and then mapped into Google Earth and exported as a KML file.

In the second phase of this experiment, the team on site at Devon Island (the "ground team") gathered eight sets of context photographs, one at the four corners of the central 180-m × 180-m square, and one at the four corners of the 500-m × 500-m square (see the flag icons in fig. 17). The ground team also followed the route described by the landing site selection team, taking photographs of each of the hazards. While gathering the photographs, the ground team also gathered ground truth notes about each of the potential hazards identified and looked for and documented any hazards the site selection team did not identify (eg, the red regions in fig. 17).

The planning team was then given the eight context photographs and asked to evaluate them for any hazards – in particular for those potential hazards that the team had previously identified. The planning team was then given the photographs of potential hazards that were taken on the route the team had described. Again, the team was asked to evaluate the potential hazards and determine whether the potential hazards were indeed hazards. As a last step before the real-time activity, the planning team was asked to record the observations team members expected to request during the real-time execution activity.

The planned real-time execution activity for the experiment, in which the team would be allowed to command the simulated robotic scout (the Humvee with the K-10 rover mounted on top; see section 3.2) to gather additional imagery of any location within the 500-m × 500-m square, did not take place due to weather conditions on Devon Island. The purpose for this exercise is to allow the landing site selection

team to determine whether any additional hazards are present and, if so, the type of the hazard. This exercise will be conducted in real time with assets at Devon Island. After a period of approximately 4 hours (the time available with the Humvee and K-10), this team will be asked to make a determination of whether this site is "safe" or not.

An additional execution activity for this experiment would have been performed if helicopter time had been available during good weather. If a helicopter had been available in good weather, two photographs of the candidate landing site would have been taken at a location comparable to the Altair pitch-up point (15-deg elevation and 1000-m slant range; fig. 14). The first image would have had no visual aids in the field of view. The second image from the same location would have been taken with visual markers at the four corners of the 180-m × 180-m square. The landing site selection team would have been asked to evaluate these images to make assess the utility of these aids during the Altair landing phase.

2.5.1 Landing Site Validation Hypothesis 1

LSV-H1: The remote observation data sets available are sufficient for planning primary landing sites.

Deciding whether a landing site is safe or not is one of the critical decisions that must be made in advance of any mission. It is also one of the most costly decisions to get wrong. If a crew determines at the last minute that the landing site is not safe, all of the resources and time spent getting there are wasted and the mission is aborted. NASA needs to know well in advance of the mission whether anticipated remote data are good enough ,or whether new precursor missions to gather additional data are needed.

2.5.2 Landing Site Validation Hypothesis 2

LSV-H2: Landing sites selected using remote observation data can be validated using robotic scout capabilities.

Even in the case in which it appears that remote observation data are sufficient to plan a primary landing site, it may be useful to use local assets to validate the landing area. By comparing the results of this experiment using only remote data to an experiment that also uses a set of local assets, we can begin to understand whether a significant gain is to be had by using local assets to increase our confidence of the safety of the landing site.

2.5.3 Additional Objectives

LSV-O1: Gather data illustrating the utility of robotically emplaced visual aids to assist with the landing of Altair.

Even if the landing site is determined safe, some hazards are likely to be present. Testing the use of visual aids to enhance the crew's ability to quickly identify the candidate landing site from the surrounding terrain and assist in the final approach and landing phase can help qualify the benefits of such aids. While such visual aids may not be required, if robotic assets are going to be present at a landing site, it would be good to know the possible improvement in situation awareness for the crew at what may be a minimal additional cost.

2.5.4 Data to be Gathered

Several metrics were gathered during the execution of the experiment to test the hypotheses described above. In addition to general PI, test director, and science team notes, 10 specific metrics (Table 10) were gathered as part of the experiment.

Table 10. LSV Data Items

ID	Description
LSV-D1	Number of identified hazards and characterization of each hazard using remote observation data
LSV-D2	Number of additional/unidentified hazards identified using simulated robotic sensors
LSV-D3	Number of hazards identified by ground truth assessments that are not identified in LSV-D1 or LSV-D2
LSV-D4	Ground truth notes and assessment (eg, zone classifications) of all surface hazards in the designated landing area

The first hypothesis for this experiment will be considered proven if all hazards identified from remote observation data are confirmed and no additional hazards are identified in any of the nine squares that are initially considered “hazard free.”

The second hypothesis for this experiment will be considered proven if either an additional hazard is detected through use of the robotic assets or if the robotic assets add significant additional information about the hazards.

3. Experimental Activities and Results

We will provide in the following sections additional information about the execution of each of the three field experiments in this study. For each experiment, we will describe items of interest that happened during the experiments, the data gathered during the experiment, the use of the data to prove or disprove the hypotheses, and the conclusions that we have drawn.

3.1 Traverse route planning and following experiment

3.1.1 Implementation

The primary way points that the PI picked for traverse this year are listed in Table 11. These way points were selected to provide the planning team with a variety of terrain types in which to plan its route as well as to include features likely to be encountered on a lunar traverse of the type being simulated. For example, segment B-C follows the rim of a crater; Way Point D is a significant outcrop likely to be of interest to the science community; Segment D-E passes through rolling terrain with some significant slopes. Most (Way Points A-E) of this route was in an area that has high-resolution Google Earth data. The original plan was for the traverse to start away from the Malapert Massif analog (the same one as for the LSV experiment) and travel to it. However, for logistical reasons (placing the early part of the traverse near the HMPRS base camp), it was decided to reverse the route. This decision turned out to be quite fortunate given the travel time (more than 90 min from HMPRS base camp to Way Point F), the PI requirement to get out to the end of the traverse area, and the less-than-optimal weather encountered this year.

Table 11. TRPF Primary Way Points

Way Point	Latitude (deg)	Longitude (deg)	Altitude (m)	Distance to next Way Point (m)	Total Distance (m)
A	75.447388	-89.904466	267	2743	0
B	75.429575	-89.836597	239	1972	2743
C	75.417903	-89.889642	235	2816	4715
D	75.415621	-89.989798	270	5752	7531
E	75.366578	-90.054889	256	2731	13283
F	75.350297	-90.127619	287	3777	16014
G	75.348039	-90.261600	280	2963	19791
H	75.321626	-90.275253	309	N/A	22754

The planning team held several meetings to discuss the best approach for planning a "safe" route using the data available and then planning the route itself. During the first meeting, the PI explained the ground rules (see section 2.3) to the team and, after that, gave the team members a chance to practice laying out routes in Google Earth. Before a second meeting took place, several members of the team submitted routes to the team for consideration. After a discussion of these initial routes, the team members decided to adopt a philosophy of trying to follow the direct line (yellow lines on fig. 18 and fig. 19) between the way points, only deviating from this direct line for areas that team members considered to be definitely impassable. By deciding to only deviate where the team was sure it was impassable, the final route (dark purple lines on fig. 18 and fig. 19) included some areas where the team was not sure the routes were passable. For these areas, the team also predetermined alternate routes (light purple lines on fig. 18 and fig. 19).

After a basic route was laid out, the team addressed the issues of classifying the terrain and deciding where to take photographs. Since routes are continuous, the team found it difficult to decide how best to document the terrain classification (refer to section 3.1.3.4 for an expanded discussion). After some discussion, it was decided that the team would simply mark points along the route – where the route was not Zone 1 – for any given category factor (slope, rock size, etc.). Slope calculations were done automatically using software that interfaced with altitude data in Google Earth (see section 2.2.4.3). Given the available bandwidth to transmit photographs, the team decided to simply standardize the interval between photographs to every 100 m, with additional photographs added to cover turns and a few suspected depressions in the terrain and areas in which the route went over the top of a rise.

Figure 18. TRPF route from planning team. The dark purple lines designate the primary routes; the light purple lines designate the alternate routes; and the yellow line is the straight line path between the PI's way points, which are shown as target symbols. The orange pin is the location of the HMPRS. The grayer area of the upper left is the area with the higher-resolution remote observation data.

To help the planning team keep track of the routes planned and the terrain classification, one of the PI's support team kept a master of routes for distribution to team members. The routes were designated using a standard notation, which consisted of the letter of the PI way point at the start of the segment and the sequential number. Thus, for the first segment, the primary route was "A0"; the first alternate route encountered was "A1"; and so on. The way points (where photographs were taken), as designated by the planning team, were identified by using the route designation, the letter "N," and a sequential number along the route. For example, the second photograph way point on the first alternate route of segment A would be "A1N02." As a result of this number scheme, the locations on which routes separate and join (primary, alternates, and alternate-alternates) have multiple designations, although they are usually referred to by the route being used at the time.

The PI gathered photographs and ground truth information on Devon Island as described in section 2. Due to weather conditions at Devon Island, the PI was only able to gather data for segments A through E and part of segment F.

Two members of the traverse team and two test directors traveled to the FFC facility at ARC for the traverse execution. On the afternoon before the start of the traverse, all four visited the FFC and decided on the final setup for the experiment. The FFC was set up using five screens; from left to right, the screens held the following data:

- Any previously displayed image that the team wanted to reference or reexamine.
- The Google Earth view of the route controlled by the team driver (the person who communicated the team decision to move).
- The photograph from the current location displayed by the other team member at the FFC once the test director gave the okay.
- A display of what was currently on WebEx (used as part of our distributed operations).
- The terrain categories for reference.

Figure 19. Alternate routes near "Malapert Massif." The dark purple lines designate the primary routes; the light purple lines designate the alternate routes; and the yellow line is the straight line path between Way Point A and Way Point B. Notice that the path points on which primary and alternate paths leave and join each other carry a designation for each path; eg, A0N06, A1N07, and A2N08.

The test director had a laptop, which was not displayed, that held the ground truth notes from the PI and an Excel spreadsheet that listed the photographs and indicated when the next photograph could be displayed.

Execution of the traverse followed the protocol as laid out earlier. For the vast majority of the photographs, the traverse team recorded their observations and then moved on while the test director recorded the times. Primary discussions not related to obvious obstacles concerned the team's ability to determine distances and object sizes from the photographs. Without the movement cues that would have been present in video instead of still photographs, the team found this very difficult. Time spent determining distance and size was a significant amount of the total time spent on the photographs. Another significant time factor was the determination of the terrain category (Table 6); this often took five to 10 times longer to determine than just the decision as to whether the area was passable or not. Additional observations about the use of the terrain classification are described later (section 3.1.3.4).

Figure 20. Location A1N03.

The team used two of its eight planned alternate routes (all were successful). The team also encountered three unanticipated obstacles (two of these blocked a primary and alternate route, which could be considered five obstacles). The locations on which alternate routes were used or impasses/obstacles were encountered are described in the following paragraphs.

Descent from Starting Point

The team encountered the first obstacle almost immediately. The planning team had already determined that there may be a problem getting down from the analog for "Malapert Massif" and had planned multiple routes (fig. 19). Photographs of the primary route clearly showed that the primary route was too narrow to pass, so the first alternate to the right was taken. This alternate route (A1; the middle one in fig. 19) appeared to be passable, although some questions were raised about the slope and size of rocks later in the route (Location A1N03); ie, alternate route (A2). The ground truth of this route was that it was marginal and the PI would not have suggested taking the route (fig. 20).

Figure 21. Obstacle near C0N03. The dark purple line is the primary route; the light purple line is the preplanned alternate. The creek to the north is impassable due to the slope of the west bank. The red line is the real-time alternate determined by the team and confirmed by the PI on site.

Slope at Creek near C0N03

The second major obstacle was encountered along the creek bed shortly after Way Point C, coming off the rim of the crater, near C0N03 (fig. 21). The team had determined that there could be a problem going down the slope from the crater, and had created both a primary and an alternate route. From the decision point, it was impossible to determine whether one route was better than the other, so by default the primary (C0) was selected. Once down the slope, it was clear that the other side of the creek bank was impassable (C0N03; see fig. 22). Although the original reason for the alternate route was concern about the slope descending from the crater rim, there was an alternate route already; so following established ground rules, the team rested at the C0/C1 decision point and started again. This alternate route had the same problem at the creek as the primary route had. At this point, the team was faced with determining an alternate route in real time. Due to weather conditions on Devon Island, it was impossible to have the PI gather this data in real time. However, the PI had provided the test director at ARC with sufficient information to determine whether the revised plan of the team would work. The team first considered continuing to the right (north) around the creek bank; however, additional photographs taken by the PI during the original photographic session were then shown to the

team and the team members, rightfully, decided this was impossible. The team's second choice was a longer route along the creek to the left to what appeared to be a flat area. This was the ground truth path around the obstacle that the PI had determined, so the team was reset to a new position (C0N04) on the primary route. The team required 7 min 40 sec to determine a new real-time route. Although the feature causing the problem was related to water flow creating a bank, the important point is that *the rapid slope change over a short distance was not detectable in the remote observation data*.

Figure 22. Location C0N03.

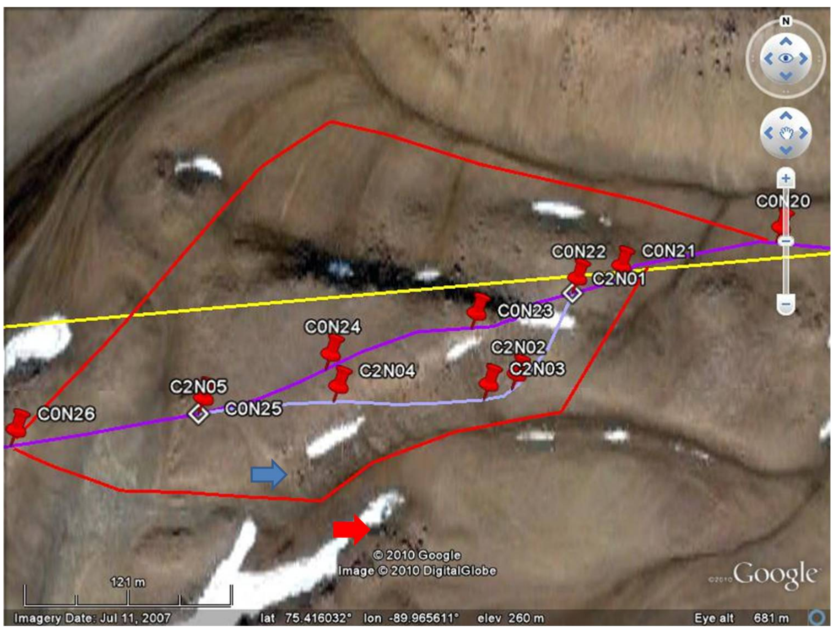

Figure 23. Routes around plateaus C0N23-C0N26. The dark purple line is the primary route (C0); the light purple line is the preplanned alternate route (C2). The dark area to the north of the routes and the ridge to the south of the C0N23 to C0N25 (along a line from the blue arrow to between C0N22 and C0N23) is too steep to ascend. The red lines are the real-time alternates planned by the team. The red and blue arrows mark objects that are referenced in the next few figures. The south route was proposed first by the team, but the test director was not sure, from the PI's notes, whether the route was passable, so the team also planned the north real-time alternate. The PI later indicated that either route would have proved passable.

<u>Slope to Plateaus C0N23-C0N26</u>

The third major obstacle also occurred on Segment C where the route encountered a plateau area, the slope of which had appeared to be climbable (fig. 23). Again, the team had determined there could be a problem at this location and had laid out both an aggressive primary route and what was thought to be a less-aggressive alternate route (C2) near location C0N22. As it turned out, the entire area from shortly before C0N23 to about C0N26 was on a plateau that had no access. The PI took additional photographs to the left and right of C0N22 that showed this slope problem; and, as team members tried routes around the problem area, they were shown these photographs. Figure 24 consists of two photographs; the right one shows the point of the plateau area as it was approached and the left shows the slope up to the plateau on the right side of the photograph after one has passed the point to the left. The red arrow is an object common to both. In the end, the team laid out two possible routes that went around the plateau. The first went to the left following the creek (fig. 24) until the route was near C0N26, where the slope up to the plateau was less steep. Due to a miscommunication between the PI and the test director, this route was ground-ruled out, although in the end it would have worked. As a second route, the team laid out a route that went up a valley to the right of the plateau. This route would also have worked. The team required 28 min to examine the photographs and to plan the two alternate real-time routes.

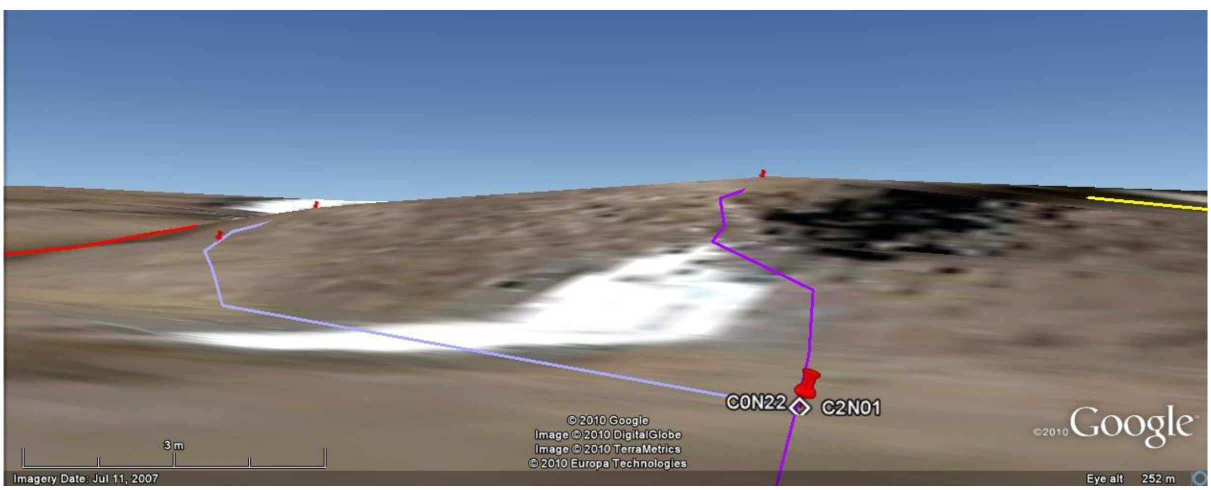

Figure 24. Approach to plateaus C0N23-C0N26. A comparison of the photograph taken at C0N22 (upper) and the Google Earth view (lower) just before that point as one approaches the outcrop that starts the plateau. As can be seen, the primary path (dark purple line) goes right into the outcrop, the extent of which was unclear in the Google Earth remote observation data. The preplanned alternate (light purple line) was marginal, so the team would have backed up slightly and swung further left (red line) to try to proceed up the valley on the left. The red arrow in the photograph marks a feature that is common to the next photograph, figure 25, which was taken in the valley.

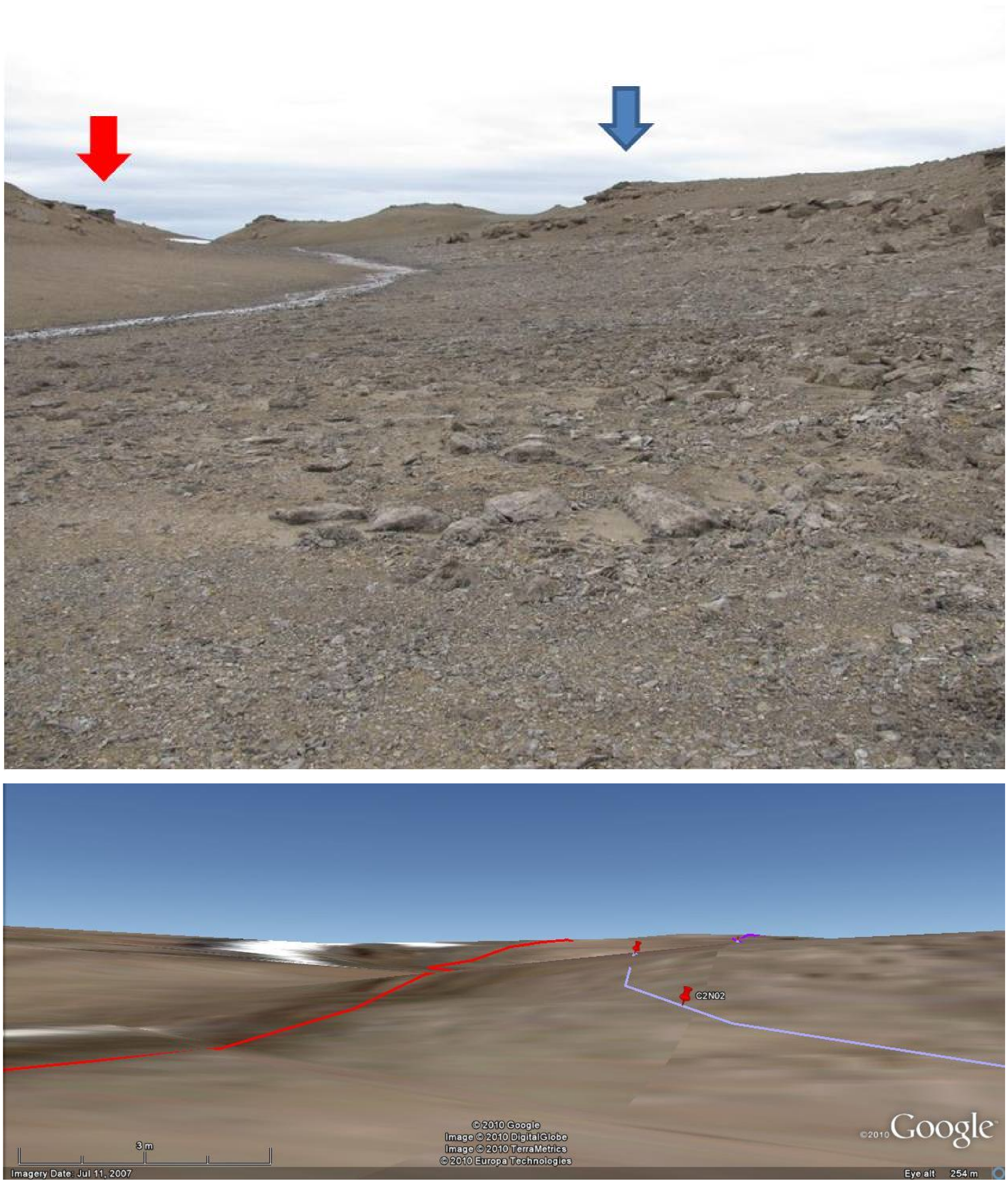

Figure 25. Valley to left of plateaus C0N23-C0N26; a comparison of the photograph (upper) and the Google Earth view to the left of the large outcrop in figure 24. The original alternate path (C2, light purple on Google Earth view) would have gone up the slope on the right of the photograph, but that was also impassable: it was too steep and there were loose rocks (everything to the right of the blue arrow). The real-time alternate path (red lines in Google Earth view, fig. 23 and fig. 24) would have gone up this valley along the stream and around the outcrop marked with the blue arrow. As can be observed, much detail is missing from the Google Earth view at this location, and it is hard to align the two views.

Slope Approaching Way Point D
The final significant obstacle was the slope on approach to and at Way Point D from location C0N29 (fig. 26). Measurements using the remote observation data had indicated a marginal, but passable, slope of about 16 deg. The team was worried about the slope, but thought from the photograph (fig. 27) that it would be possible to approach at least a little close to the object or, at worst, have to back up and proceed down the slope to the left (gray-colored area on fig. 26 and fig. 27, and as also indicated by the red line on the latter). However, the ground truth slope was closer to 29 deg, including a ledge-type obstacle to the right. After being informed of this, the team quickly decided on a proceeding down the slope to the left, bypassing Way Point D and joining up with Segment D about 50 m under Way Point D. The slope near Way Point D is seen in figure 28.

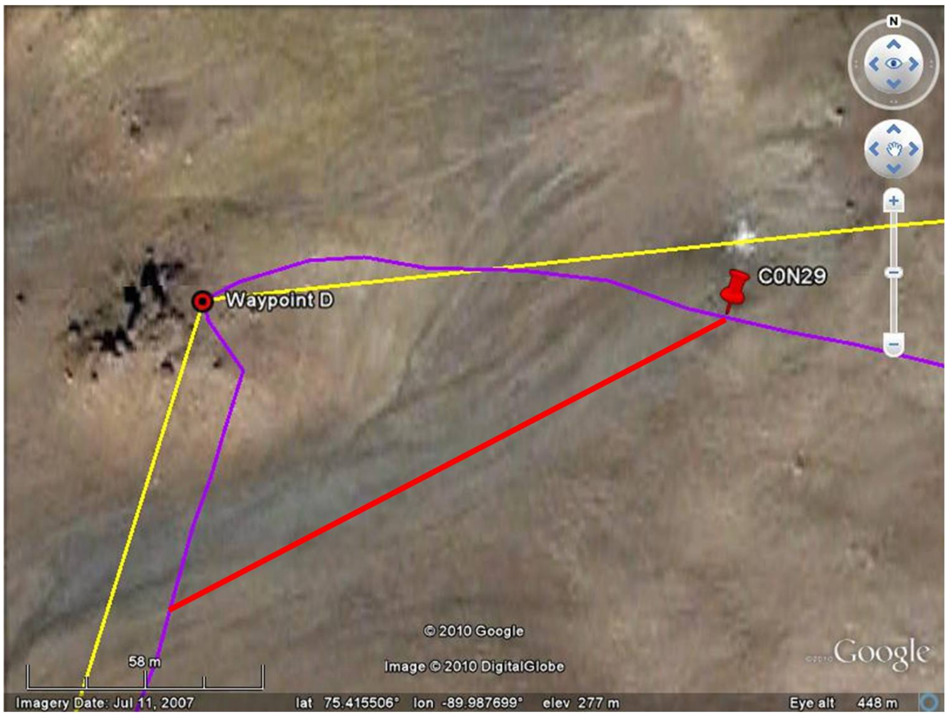

Figure 26. Way Point D from overhead. The dark purple line is the primary route; the yellow line is the straight line connection between the PI's way points; and the red line is the real-time alternate path the team selected to bypass the steep slope when approaching Way Point D from location C0N29.

Figure 27. Way Point D from C0N29.

Figure 28. Way Point D from below.

Summary

In summary, this team planned a traverse of 23.8 km, passing through eight specified way points. Conditions in the field allowed 15.7 km to be traveled and photographed. Two planned alternate routes were used and three unanticipated obstacles were encountered over this 14.8-km distance. However, the team was able identify a negotiable path around all of the obstacles. These and other results are tabularized in the following section.

A debriefing was held at the end of each day (the points that were raised during the debriefings are discussed in section 3.1.4).

3.1.2 Data Gathered

Table 12, the tables that are referenced in Table 12, and the rest of this section summarize the data gathered to evaluate hypotheses and form the basis of the observations and conclusions in later sections.

Table 12. TRPF Data Gathered

ID	Description	Value
TRPF-D1	Nominal route length compared to straight-line distance between way points.	• 23852 m vs. 22749 m • Terrain factor: 1.048 • See Table 13 for breakdown by segment
TRPF-D2	Maximum route length (ie, all worst-case alternate routes) compared to straight-line distance between way points.	• 23964 m vs. 22749 m • Terrain factor: 1.053 • See Table 13 for breakdown by segment
TRPF-D3	Number of alternate routes required as determined by the route planning team during the planning phase	• Eight total • Seven branches from primary (A1, C1, C2, D1, D2, E1, and F1) • One branch from an alternate (A2)
TRPF-D4	Net speed across the entire route. Net speed" in this usage is the total time required by the traverse team to assess, decide, and issue commands at nominal planning points along the traverse route (ie, each picture presented to the team at the designated points on the route). Note: By ground rule, the maximum allowed speed was 5 km/hr.	• A total of 2.09 km/hr over the initial route followed • It is the test director's opinion that discussions to assign a terrain zone category accounted for the majority of time spent on each surface-level image, and that the actual passable/impassable decision rarely would have required more time than allotted under the allowed maximum speed (5 km/hr) • See Table 14 for a further breakdown of data
TRPF-D5	Time required to assess, decide, and issue command on unplanned anomalies	• C0/C1 creek (impassable slope): 14:00. • C0/C2 plateau (impassable slope): 28:10 (could be considered two re-plans due to test director ruling on first re-plan). • C0N29 steep slope: 4:29 (or 14:46; see daily table).
TRPF-D6	Number of alternate routes used	• Two alternates (A1, C2) selected from photographs. • One additional alternate (C1) was used after the primary (C0) was found to later be impassable. • Note: Two of the alternates used (C1, C2) were impassable, leaving no alternate routes. • Note: Decision F0/F1 never occurred as that part of the traverse was not executed. • Note: An additional alternate (A2 from A1) should have been selected, but the problem with the route was not seen.

ID	Description	Value
TRPF-D7	Number of unplanned anomalies encountered	• Three anomalies (C0/C1 creek; C0/C2 plateau, C0N29 steep slope). • The first two anomalies blocked both the primary and alternate routes; this could be counted as 5 anomalies.
TRPF-D8	Ground truth notes and assessment (eg, zone classifications) of the straight-line route between way points and the planned traverse route	The PI's assessment of conditions on the ground is that the planning team made some very good choices for the route selected, and that following the straight-line path between way points would not have significantly improved the speed or trafficability of the route. The planning team also assigned appropriate zone classifications during both the planning stage and the ground-level photograph evaluation stage. Descending from the first way point would have been best accomplished using the second alternate route as this would have avoided complex terrain due to rocks and slope (this is a good example of where a compound classification would have been more accurate). The remainder of Segment A-B included the diversion across the airfield and the entry to Segment B-C. The planned route along Segment B-C was appropriate. A route following the streambeds along Segment C-D would have been faster and avoided at least one of the obstacles. This statement is also true for Segment D-E, which was chosen to cross some obvious rolling terrain. Attempting to follow the straight-line route in this segment would have been more difficult ,and would likely have encountered other impassable obstacles (this is somewhat speculative as I did not attempt to precisely follow that route, but obstacles were obvious along that path as we followed the planned route). Segment E-F and that portion of Segment F-G that was completed could both have followed closer to the straight-line route without encountering obstacles, but this route was not significantly shorter than the planned route.
TRPF-D9	Number of changed zone classifications due to improved understanding provided by surface-level imagery	It is not possible to quantitatively evaluate this metric as the remote observation data were not sufficient to distinguish between the lower zone classifications. With the proper distance/size queues, it was possible to accurately classify the terrain zones along the path for the non-slope criterion. Even with distance/size queue, it was difficult to accurately judge the slope. See also section 3.1.3.4.
TRPF-D10 (new)	Time required to assess, decide, issue command, and execute traverse down the alternate route	• A0/A1 – 1:51. • A1/A2 – 6:00. The decision to use A1 was probably incorrect according to the PI. • C0/C1 – 3:15. The discussion centered on the lack of view of the creek, not which route was better. • C0N03 (unexpected) – 7:40. • C1N02 (unexpected) – 3:40. • C0N03 and C1N02 (real-time alternate) – 14:00. • C0/C2 6:29 at C0/C2, but much discussion about feature itself; decision was easy. • C0N23 (unexpected) – immediate, go back to alternate (C2).

ID	Description	Value
		• C2N04 (unexpected) – 8:47. • C0N23 and C2N04 (real-time alternate) – 28:00. • Way Point D (unexpected) – 4:29. • D0/D1 – 3:06. • D0/D2 – 2:02. • E0/E1 – 5:13.

Table 13. Terrain Factors for Routes

	Straight (m)	Primary (m)	Factor	Alternative (m)	Factor
A-B	2743	2816	1.027	3156	1.151
B-C	1972	1975	1.002	1975	1.002
C-D	2815	2850	1.012	2905	1.032
D-E	5751	5955	1.035	6059	1.054
E-F	2730	2806	1.028	2903	1.063
F-G	3776	4430	1.173	3946	1.045
G-H	2962	3020	1.020	3020	1.020
Total	22749	23852	1.048	23964	1.053

Table 14. TRPF Data Gathered – Speed

Session	Route	Distance (m)	Time (min)	Speed (km/h)
Tue AM	A0 (A0N01-A0N02) A1 (A1N01-A1N06) A0 (A0N06-A0N27) B0 (B0N01-B0N20)	2892	116	1.50
Tue PM	C0 (C0N01-C0N16) C1 with second reset	1963	76	1.55
Wed AM	C0 (C0N17-C0N22) C2 (C2N01-C2N04) C0 (C0N23-C0N29) Bypass to D D0 (D0N03-D0N43)	4976	158	1.89
Wed PM	D0 (D0N44-D0N63) E0 (E0N01-E0N27)	4931	74	4.00
Total		14762	424	2.09
Alternates				
Thu AM	D1 (D1N01-D1N18) E1 (E1N01-E1N08) A2 (A2N01-A2N07) F0 (F0N01-F0N11)	4043	64	3.79
Total with Alternates		18805	474	2.31

3.1.3 Hypotheses and Objective Discussion

3.1.3.1 Traverse route planning and following hypothesis-1

TRPF-H1: The available remote observation data sets of a region to be traversed are sufficient for planning primary and alternate routes for the traverse.

The hypothesis will be considered true if *all* of the following are true:

- No hazards are encountered that were not apparent from remote observation data (ie, TRPF-D7 is zero)
- Ground truth assessments of the traverse route trafficability agree with the planning team assessment (ie, TRPF-D8 assessments indicate that the route planning team correctly interpreted the surface features indicated in the remote observation data)

The remote data were insufficient to plan the route. There were cases in which the remote data were insufficient to detect slopes that made the location impassable.

3.1.3.2 Traverse route planning and following hypothesis-2

TRPF-H2: Robotically implemented traverse route execution will require surface-level imagery to identify and maneuver around local hazards/obstacles.

The hypothesis will be considered true if *any* of the following is true:

- Surface-level imagery reveals that suspected hazards, based on remote observation data, are sufficiently severe to require the use of an alternated route (ie, TRPF-D6 is greater than zero)
- Hazards are encountered that were not apparent from remote observation data (ie, TRPF-D7 is greater than zero)
- Ground truth assessments of the traverse route trafficability agrees with the planning team assessment (ie, TRPF-D8 assessments indicate that the route planning team correctly interpreted the surface features indicated in the remote observation data)

The hypothesis is definitely true, as both of the first two evaluation criteria are true (only one of the three needs to be true); ie, both TRPF-D6 and -D7 are nonzero.

The assessment of the final evaluation criteria is more subjective; but all members of the team were in agreement that with information comparable to the photographs, they would have been able to navigate around all of the hazards/obstacles encountered. The PI agrees with this conclusion based on conditions encountered on the ground along the entire planned route (as much as was completed in the field).

3.1.3.3 Traverse route planning and following hypothesis-3

TRPF-H3: Route traversing efficiency will improve in direct proportion to the number of surface-level imagery sources used to support a traverse.

Figure 29. Parallel sections of routes D0 and D1. Photograph locations along two sections of D0 and D1 that just happen to be nearly parallel and, thus, are useful for a qualitative test of TRPF-H3.

The hypothesis will be considered true if *all* of the following are true:

- TRPF-D4 for Group B is less than that for Group A
- TRPF-D5 for Group B is less than that for Group A

As mentioned in the initial description of the hypotheses, we decided, after the original protocol was reviewed, not to split the execution team into two groups and did not explicitly gather multiple views. However, due to the primary and an alternate route that the traverse planning team picked for segment D, there was an area near where the primary (D0N55-D0N57) and alternate (D1N15-D1N18) rejoined (D0N58-D1N19) in which photographs that were approximately parallel to each other were taken (fig. 29).

The team took advantage of the multiple screens in the FFC to display images from both the primary and the alternate routes on neighboring main screens and compare them. The three pairs of photographs, one from each route, are shown in figures 30 and 31. The problem noted above with images being taken approximately every 100 m was an even more significant problem for photographs taken from two different angles. It took the team a significant amount of time to even decide which objects were common in the two images.

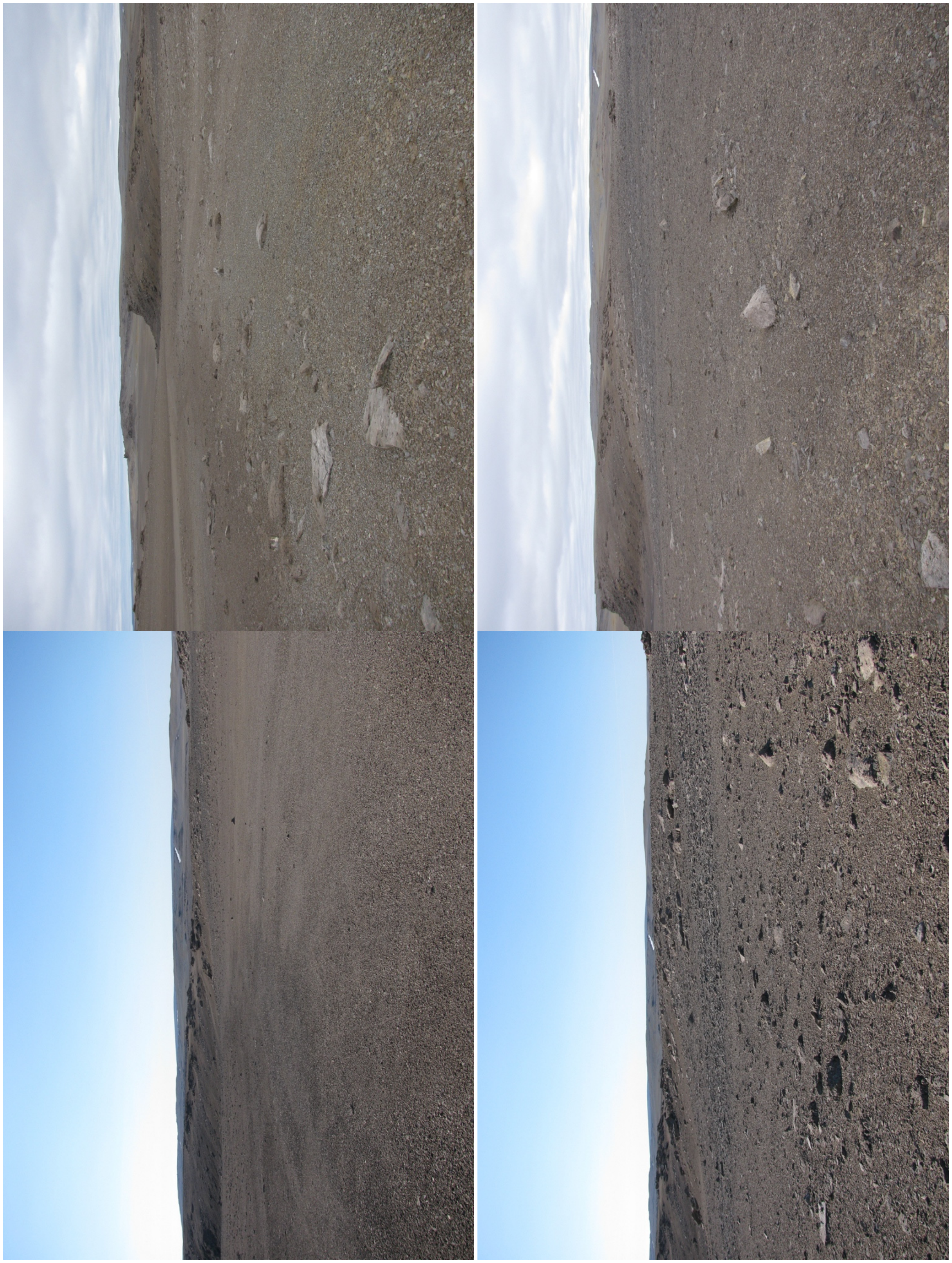

Figure 30. D0N55 and D0N56, and D1N15 and D1N16. D0N55 (left) and D0N56 (right) are closest to the caption; D1N15 (left) and D1N16 (right) are farthest from the caption. Notice the relative position of the snowfield. Although D0N56 (lower left) was taken to the left of D1N16 (upper left), the snowfield is farther right in the frame of the photograph, indicating that the photographs were not taken parallel to each other.

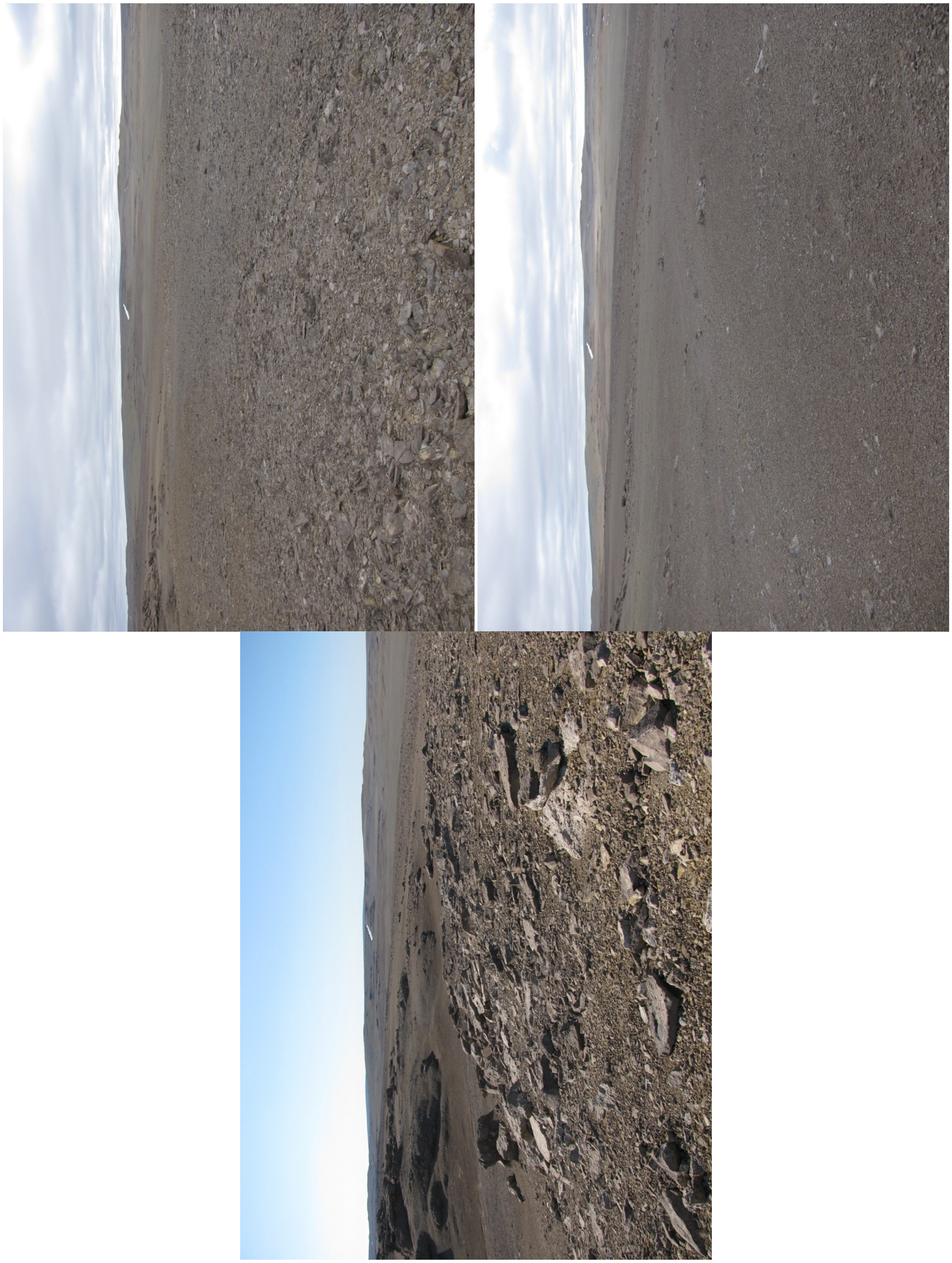

Figure 31. D0N57, and D1N17 and N1N18. D0N57 is closest to the caption; D1N17 (left) and D1N18 (right) are farthest from the caption. D0N57 was taken farther along the route than D1N17 (upper right), so the rocks seen on the left of D1N17 are probably near the location of D0N57.

The team found that it was much more difficult to compare the two images than its members had imagined. It is suspected that using two views would have actually taken longer. It should be noted that these photographs were not explicitly taken for this purpose and, thus, were not aligned and did not have any specific supporting information.

If the original plan of using two offset rovers had been followed, it is not clear that this would not have led to longer evaluation times instead of shorter ones. We suggest that if a future test wishes to use multiple rovers in this manner that a thorough pretest investigation be performed to determine how to use two views, the additional information that is needed, and an evaluation of the offsets or relative angles needed.

3.1.3.4 Additional assessments

Surface-level Imagery vs. Remote Observation Equivalent

Although the combination of remove observation DEM and imagery is useful, it does not provide the full context needed. A few examples that we ran into in this experiment, showing the difference between the surface level and remove observation data, are given below.

Since the remote observation DEM is an average over a range, it does not often accurately indicate changes in slope on ridges and valleys. Location A0N22 is on a ridge that was traversed perpendicular to the run of the ridge. The profile of the ridge in Google Earth was such that it was expected that, from the location, it would be possible to see the next location at the bottom of the valley. As can be seen in figure 32, this is not the case as the top of the ridge as flatter and has more of an edge to it (but is still passable). There were also similar smaller scale problems in which a rise of 2 m on an otherwise flat area would hide the terrain for tens of meters. As the weather did not allow for real-time imagery, the test director simply exercised a ground rule as to whether or not the team could proceed in such cases based on the information provided by the PI prior to this implementation phase with the traverse planners.

Another case is for specific formations that change over distances small than those represented by the DEM. Figure 33 is a side-by-side comparison of the image of Way Point D taken by the PI and the corresponding “view” from Google Earth. The extent of the slope around clearly averaged out in the Google Earth view due to the course grid for the DEM.

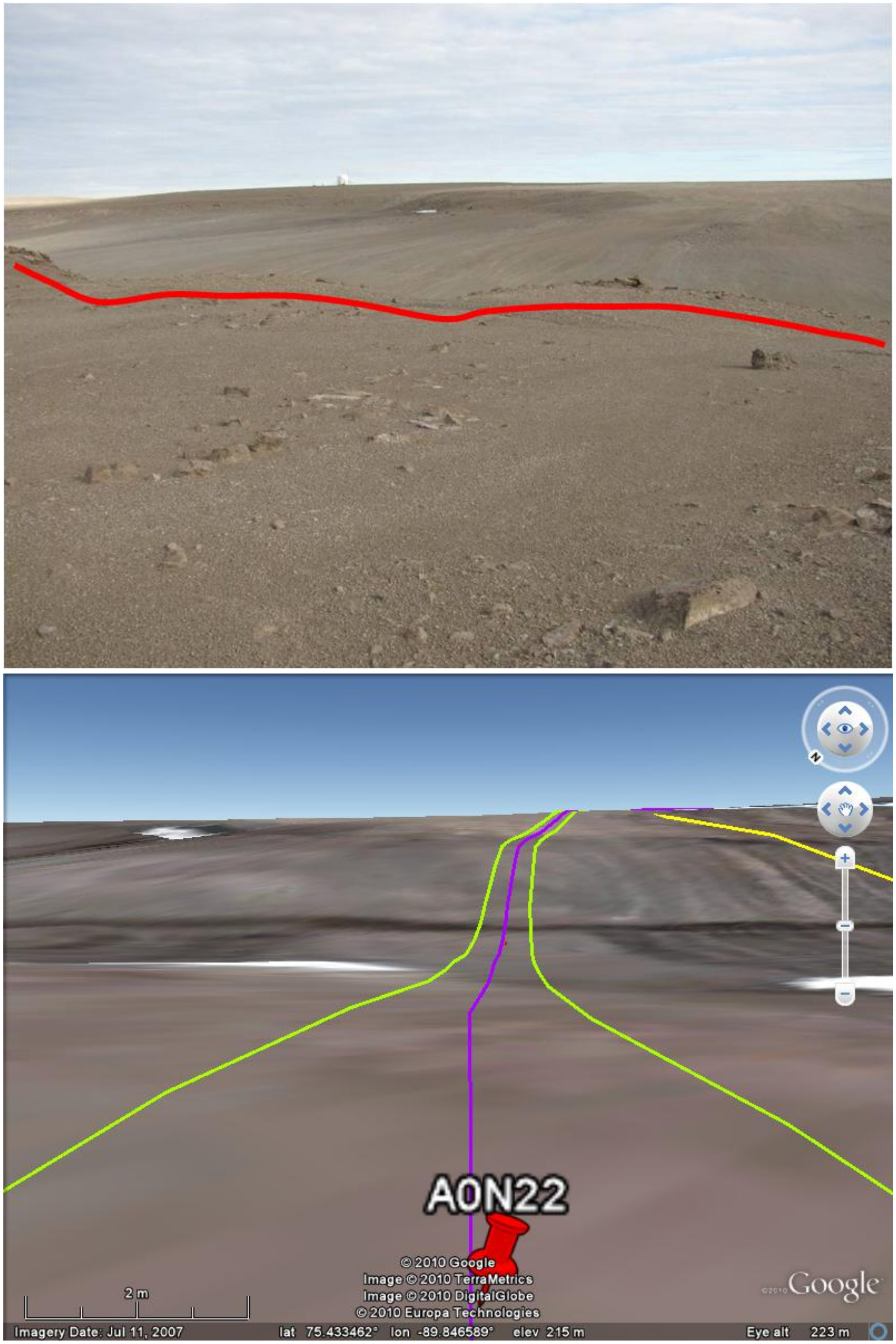

Figure 32. Location of A0N22 photograph vs. Google Earth.

Note how the ridge prevents someone from seeing the creek between here and the hill on the other side of this small valley. The red line has been placed just below the ridge to draw attention. Note that the top photograph is rotated clockwise slightly compared to the bottom image, as can be seen from the location of the upper snow patch in each.

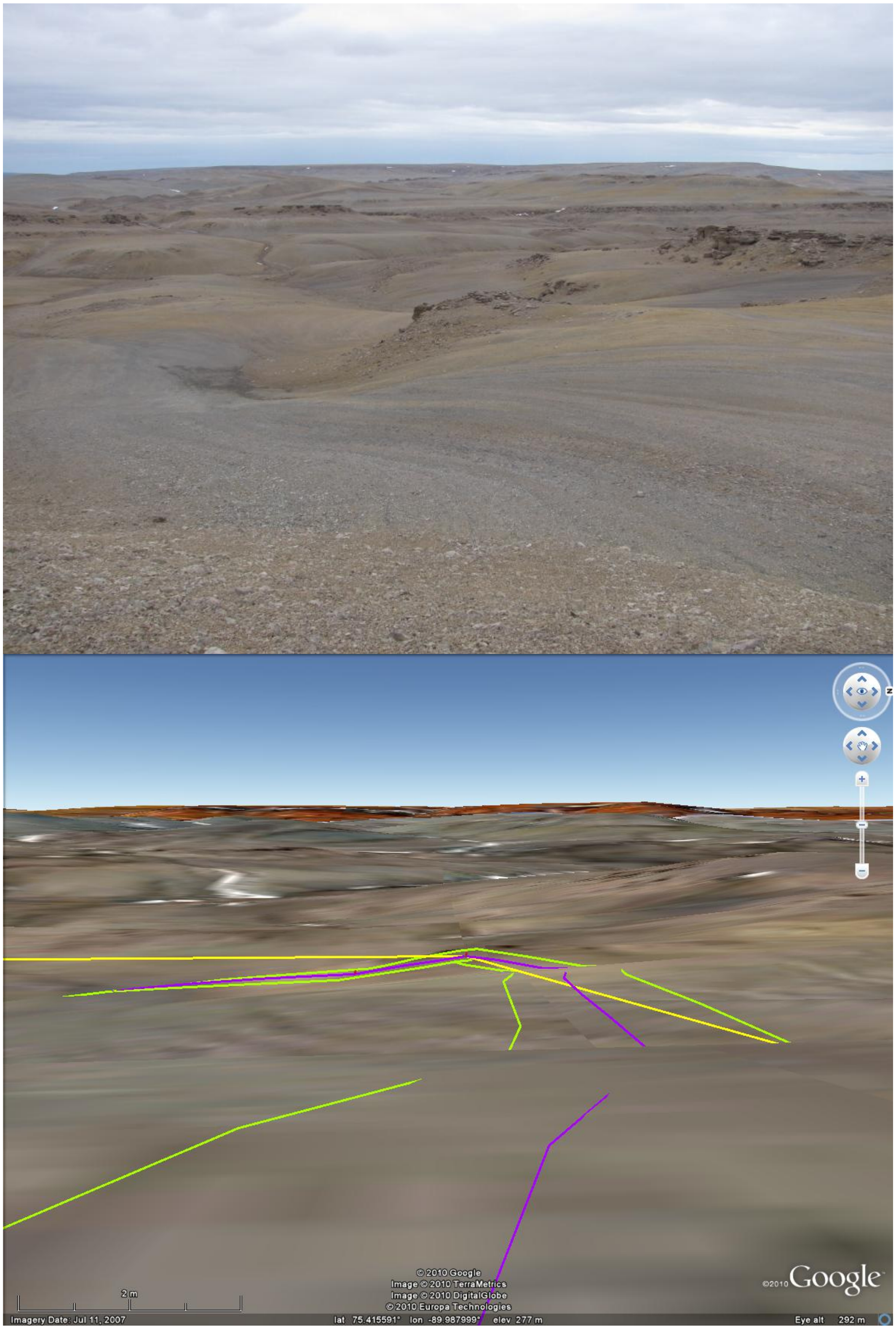

Figure 33. Way Point D photograph vs. Google Earth from C0N29.

Notice how the outcrop (Way Point D) in the upper photograph is averaged out in the DEM available in Google Earth.

Judging Distances and Slopes

As mentioned earlier, the team found it difficult to judge distances and slopes without additional information. This seemed to be particularly true in open areas approaching a slope. In figure 34 are two sequential photographs taken at locations E0N17 and E0N18, 102 m apart. The slope in the foreground of E0N17 is only about 15 m away, yet the team judged it to be after the next expected photograph, or 100 m away. The second photograph clearly shows that this location is on top of the initial slope. It is also difficult in the E0N17 to see that there is a flat region between this first rise and the rises beyond; while this flat region is clearly present in E0N18. Further, the team did recognize that the this initial rise had a slope that was greater than 15 deg, which was nearing the 20-deg limit set in the ground rules.

Figure 34. E0N17 and E0N18.

The initial rise in the upper photograph is only 15 m distant and has a slope of 17 deg. The rise also hides a significant area before the hills in the distance.

Use of Terrain Zone Categories

Defining a path and before classifying a zone: Defining your path wide enough for your vehicle to traverse (with margin) allows a more focused evaluation. Over a large area (vehicle or scout imagery), large areas of impassible or difficult terrain may be encountered, but a clear path also may be found through or around these obstacles. The terrain zone classification should be made based on the path, not the overall area, to keep from over constraining your traverse route.

Slope should be classified by steepest path segment: There is a possibility of wide variations in slope magnitude over any given path segment. While some of these slopes may be very short, they could still limit the traversability of the path. Slopes can be hard to measure from images and visual observation alone, especially at distance. Slopes in question should be reevaluated with instrumentation prior to and while traversing. In addition, the classification as currently stated does not specify the direction in which the slope is measured; this could be in the direction of travel (assumed for the measurements made in the field for this experiment) or at some angle with respect to the direction of travel. During this experiment, we observed several instances in which slope measured in the direction of travel would have placed this area in one of the lowest classification zones. But at this same location, the slope measured perpendicular to the direction of travel was quite steep, which would have placed this area, in the highest (ie, do not enter) classification zone in many of these instances. Cross slopes should thus be taken into account to form a compound slope measurement, not simply the slope in the direction of travel.

Rocks classifications should be broadened to obstacle height: Other terrain features such as trenches, wash-boarding, etc. are not explicitly covered in the current classification scheme. These features need to be accounted for and, like rocks, can be classified by their size and number density. There could also exist a case in which a rock may be only 15.24 to 30.48 cm (6 to 12 in.) thick but is imbedded in the terrain at an angle or in such a way that the distance from the top of the rock to the surface is much greater. The rock should be measured by that distance in this case.

Percent rock coverage is too vague: This criterion assumes an unspecified area in which to measure a density. However, there may be a thin line of obstacles crossing the direction of travel that makes it impassable. Referring to an earlier comment, the percent coverage should be evaluated in the direction of travel with some distance included to the left and right of this path to allow for adequate movement of the vehicle. The zone classification assessment should be made at the worst-case location along this path.

Some predetermined matrix should determine overall zone classification based on a combination of sub-zones: Simply taking the highest zone classification as the overall zone may not be sufficient. For example, if there is a moderate density of 30.48- to 45.72-cm (12- to 18-in.) rocks covering an 18-deg slope, this would receive a Zone 3 rating. However, that terrain may still not be passable. There may be a need for a correlation matrix showing the compound ranking based on the subclassifications.

Table 15. Suggested New Terrain Zone Classifications

Description	Zone 1	Zone 2	Zone 3	Zone 4
Maximum slopes (deg)	0-5	>5	>15	>20
Maximum small (< 15.24-cm [6-in.]) obstacle density*	TBD	TBD	TBD	TBD
Maximum medium (15.24- to 30.48-cm [6- to 12-in.]) obstacle density*	TBD	TBD	TBD	TBD
Maximum large (0.3- to 0.61-m [1- to 2-ft]) obstacle density*	TBD	TBD	TBD	TBD
Maximum very large (> 0.61-m [2-ft]) obstacle density*	TBD	TBD	TBD	TBD
Soil mechanics	Firm	Soft	Loose	Very Loose

*Density should be calculated using an area defined as the wheelbase of the vehicle long path.

The TBDs should be filled in based on the capabilities/size of the vehicle being used. A generic matrix that could be used for any vehicle is desirable (but not considered likely); and if alternate classification definitions can be found that allow this, they should be considered instead of the categories shown here.

3.1.4 Traverse Route Planning and Following Conclusions and General Observations

During the execution of this experiment and the analysis and discussion of the data from it, we made the following observations and came to the following conclusions:

- Remote observation data are insufficient to plan a definitive route (TRPF-H1), that is completely free of undetected obstacles that would stop vehicles of the type assumed here. Sections of the planned route were impassable. The primary type of obstacle that was encountered was steep terrain – cliffs, large outcrops, walls, etc. While remote observation data were marginal for detection of obstacles such as rocks, there were no sections that were impassable due to rocks alone.
- Surface-level imagery, which provided a significant improvement in the knowledge of the route, was required to complete the traverse (TRPF-H2). All of the major obstacles were identifiable in the surface-level imagery. While some of marginal cases were not immediately seen, they likely would have been detected had real-time, full-motion, surface-level imagery been available. As with the remote observation data, determination of slopes was the most difficult problem to detect and evaluate.
- The original proposed field test concerning multiple views (TRPF-H3) was not implemented due to insufficient time in the field. However, based on some limited opportunistic data, it appears there is a concern that it may take too long for the "drivers" to correlate multiple views. Additional work needs to be done on exactly how multiple views would be used and the imagery can be quickly correlated. But, given the results from this opportunistic experiment, any additional work in this area should be considered low priority.

The team and PI also made a number of general observations as follows:

- The Terrain Zones Classification System appeared to be useful for classifying large sections of terrain, but its use for a specific path and its evaluation during the execution of the experiment were problematical. (We also remind the reader of the full discussion on these points in the previous section).
    - Evaluators thought it was useful as part of their thought process to use the terrain zones to help them determine whether the route was passable. However, it is the Test Director's observation that the terrain zone evaluation and its documentation significantly reduced the effective speed. There appears to be no good method for separating the execution of this process into two different time periods to separate out this effect. An alternate would be to run multiple groups through this exercise; some classifying the terrain and others just deciding a go/no-go to next point.
    - A fuller explanation of why the zones are defined the way they are would be useful. It was not clear why the percentages were set the way they were in the classification table and what these percentages were meant to cover; ie, entire area in front of the vehicle or just a path forward. In particular, the lower percentages tended to create what the team saw as "zone inflation"; that is, a higher zone category, but not necessarily a lower speed. It may be useful to try to tie the zones to some percentage of a maximum vehicle characteristic, such as speed or energy use, to create a more intuitive classification system.
    - The following particular ideas might be included as part of a classification:
        - The use of "obstacle" instead of "rock" to also account for dips and bumps.
        - There were areas of structured terrain that would impact operations.
        - There were cases in which a rock was near a dip in the ground that would cause a greater differential height across the vehicle.

    - A factor related to “wear and tear,” such as the damage inflicted by the sharpness of the rocks, might also be included.
    - A traction criterion is probably needed for “soil” in addition to softness, as is a consideration for compound terrain.
    - A question that might be considered is: If the three classifications are Zone 2, should the overall evaluation of the terrain be Zone 3?
    - Or, the fact that small rocks on level ground are not as big a problem as having them on slope as the loss of traction is less.

- Although the surface imagery was sufficient to carry out the experiment, the “driving” and evaluation of the route would have been much easier if additional information had been directly available to help interpret the photographs.

    - Some sort of distance or size queues are clearly needed in the photographs. This could be achieved either by projecting additional information on the photographs or having or projecting known queues into the scene when the imagery is taken. Use of video instead of still imagery (an analog implementation limitation) would have given some additional distance/size queues, but it is unclear whether those queues would have been sufficient. Another approach would be to use a scanning range-finding device (eg, a laser) to determine distance and then overlay the results on the imagery.

    - Slope measurements need to account for cross-track slopes. The original planning analysis only calculated slopes along the direction of travel. The ground truth showed that there were several locations in which the cross-track slope was significant – in some cases much steeper than the slope along the direction of travel.

    - There needs to be a more automated mechanism to display imagery and additional meta-data from the remote site that the team executing the traverse is allowed to see. For example, the slopes measured at the surface-level imagery location should display with the photographs. Similarly, better software support of for the use of multiple screens would allowed both the current and the previous photograph to be displayed and changed with a single command. Overlay of route on the photograph would be useful. The vast majority of the routes should have been straight ahead for the next segment. The evaluators mentioned that the overlay would still be useful to see upcoming turns past the next point.

- The next time this experiment is executed, the following additional ideas should be evaluated as changes to the implementation:

    - We can expect that an actual traverse team would have had some practice time with the type of data they would be using. Follow-on executions of this protocol should have a set of representative data for the traverse team to use during a familiarization exercise, particularly so the team can get familiar with distance, size, and slope queues.

    - By acknowledging that the use of multiple still images for this experiment was the result of logistical constraints, if this approach were to be used for an actual traverse, it would be shown that the distance of 100 m between surface imagery locations was too large. The team is usually looking or concentrating on the next 25 to 50 m. While the photographs were taken at a resolution that allowed zooming, the additional time needed to zoom in the images was usually not taken. Several locations on hills (especially the descending side) and even flat areas with minor local rises (2 to 3 m) led to part of the route not being visible in the imagery. Although ground truth showed these were not problem areas, it did lead to loss of situational awareness and increased evaluation times. Thus, given the bandwidth limitation for this experiment and the manner in which the teams used the imagery, more frequent but lower-resolution images would have probably worked better than less frequent but higher-resolution images.

- The photographs required a great deal of time to acquire. Given the above observations in the previous bullet, an alternate implementation method for the field would be to use a video camera and extract photographs from the video at required locations. This could speed up data acquisition. It would also allow for later additional investigations by varying the frame rate or distance between images to determine a minimum set of values for or an optimal trade off between bandwidth and needed knowledge.

3.2 Opportunistic science protocol experiment

3.2.1 Implementation

The remote science team was provided with the following assumptions and ground rules:

a) The targets are selected by the science community and are "mandatory" for the K-10 science team (ie, these targets were selected to support this experiment and switching to a "more interesting target" would not necessarily support the objective of this experiment).

b) It is recognized that these in reality targets all share a common regional context (the targets are not entirely unrelated). That said, the science team should bear in mind that we are dealing with a cold climate and impact crater setting in which some targets might be out of their original context. In that sense, the science team should be open to examining each target somewhat independently of the others (eg, on the Moon, boulders in a given area might have all come from the same place or be ejecta from distant impacts).

c) The targets need to be examined in the exact order presented by the Test Director and Field Representative for two reasons: (1) approach images to each target will be revealed only when the investigation of the previous target has been completed; and (2) specific approach directions need to be adhered to, to minimize the environmental impact of our rover on the site.

d) At each target, the science team needs to reach a point where it either: (1) considers that it has achieved *adequate understanding of the nature of target* to move on to the next; and/or (2) has exhausted what it can learn about the target given the payload on the rover or what the science team would consider a reasonable amount of time and effort expended on that target (judgment call by the Science PI). *Adequate understanding of the nature of the target* is defined here as sufficient knowledge about the target to determine its basic nature (rock type, origin), to place it on a geologic map (context), and to have reasonable hypotheses concerning its history and significance in the geologic evolution of the region.

e) The Test Director will, among other things, log the time spent by the science team investigating each target. Investigating *nearby sub-targets* of the science team's choosing is allowed (and will be included in the time needed to investigate the prime target) if the science team feels that examining these sub-targets is critical to its investigation of the prime target. "Nearby" is defined as no more than two times the size of the prime target away from its edge (ie, for a 5-m boulder, "nearby" is "within 10 m of the edge of the boulder").

f) The rover can in some cases, at the science team's request, position the microscopic imager directly over the target.

3.2.2 Data Gathered

The target objects investigated were chosen approximately 1 week before the schedule field test by the PI (Pascal Lee) in one of the three areas previously selected for investigation by the K-10 science team at Haughton Crater (Site A in fig. 13). Use of the area selected by the K-10 team allows this experiment to leverage a wireless network set up to support the K-10 team.

To conduct the OSP experiment, Eleven target objects (fig. 35) were selected covering three size scales: 2.5, 25, and 250 m. The number of targets selected and the range of size scales considered were determined by the time available for the OSP experiment during the HMP-2010 field campaign and the geologic features available and accessible within Site A during that time. The nature of the target objects was varied. They included boulders whose largest dimension was on the of order 2.5 m, debris field and colored soil patches with a diameter of approximately 25 m, and larger geologic features such as a valley head area approximately 250 m across. Although 11 science targets of opportunity covering three size scales (2.5, 25, and 250 m) were identified in the field in preparation for the OSP experiment, only six were actually investigated by the remote science team due to time constraints on the experiment. The six targets investigated still covered the original three size scales. The list of target objects investigated for this experiment is given in Table 16.

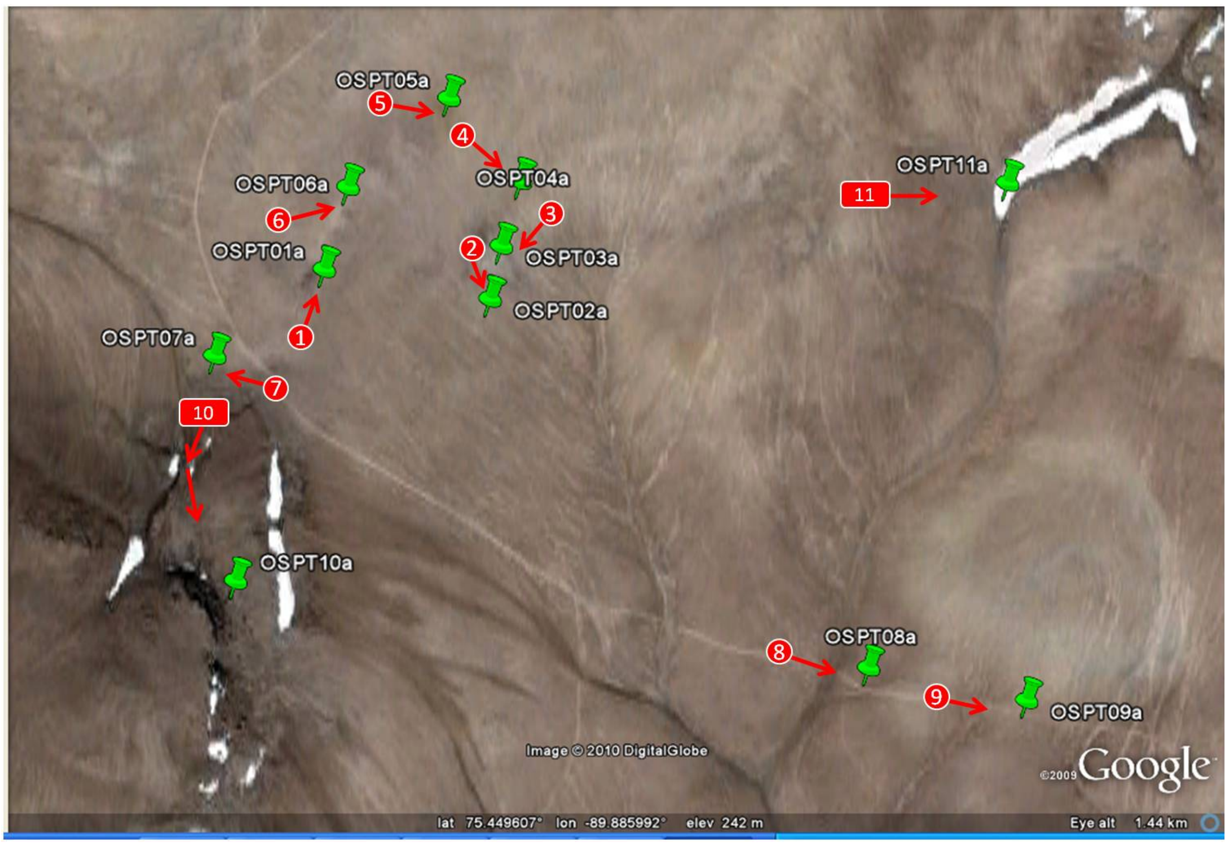

Figure 35: OSP target locations.

The green pins are the nominal locations of the OSP targets of interest. The numbered red circles indicate the approach photographs that were shown to the science team.

Table 16. OSP Targets Investigated

ID	Size (m)	Description	Latitude (deg)	Longitude (deg)
OSPT01	2 x 1.3 x 0.7	Boulder (in block field)	75.45050	-89.89950
OSPT03	25 x 20	Patch of light-colored surface rubble	75.45067	-89.89233
OSPT04	5 x 4 x 0.5	Boulder (isolated rock slab)	75.44617	-89.87100
OSPT05	25 x 8	Patch of orange soil	75.45217	-89.89450
OSPT06	2.3 x 1.4 x 1.1	Boulder (in block field)	75.45133	-89.89683
OSPT11	250 x 50	Valley head area		

For each target object, the small pressurized rover analog was first positioned at a distance at which the entire object could be imaged in a single 40-deg FOV frame. As an initial condition prior to the investigation of each target object, the science team was given the position (coordinates) of the object so the team would know where the object was located in relation to its context in satellite imagery, and was shown the single 40-deg FOV color image, which served as the "initial approach" image to the target of opportunity. From this initial information, the team decided first whether the object warranted further investigation. If it did, the team decided on an initial observation plan for the object. To execute this observation plan, the team would provide voice commands to the Humvee driver to position the vehicle as if it were a small pressurized rover operated in tele-operated robot mode, and to the K-10 sensor operator to acquire data. The science team then evaluated the observations as data came in and decided whether modifications to the observation plan were needed. If so, the changes were again "uploaded" (communicated by voice).

The Humvee operator (Pascal Lee) recorded an annotated time log in the vehicle to document the sequence of executed commands and any breaks in simulation that would ultimately have to be corrected in estimating actual science operations times. The Test Director (Stephen Voels) collocated with the science team at NASA ARC to record an annotated time log that started when the team was shown the initial image and ended when the team decided to move on. The science team was also asked to keep a log of its science decisions as to which instruments to use and to document its findings for each object. This process was repeated for each new object until time expired for the experiment. Figures 36 and 37 show the use of the SPR analog examining targets at the lower and upper size scales examined.

The data summary required to evaluate the hypothesis is summarized in Table 17. In addition to the original data required, we have also included the number of times the science team cycled through its decision on which observations to make.

The following additional information should be taken into account when interpreting the data in Table 17.

- Second guessing by the science team was a significant time factor in deciding not to do further work on OSPT06.
- Estimates for all but OSPT11 are based on corrected times with fault time subtracted out.
- The estimate for OSTP11 is based on ignoring initial communications direction problem and two additional rounds of PanCam.
- A number of science cycles were added as a data point; need to account for analysis of intermediate results that changed the initial plan.

Figure 36. OSPT04.

Examination of OSPT04 (flat rock, 5-m scale, lower right) using the microscopic imager, which is mounted to the rear bumper of the Humvee.

Figure 37. OSPT11.

Examination of OSPT11 (valley head, 250- m scale, middle left) using the Gigapan mount to the roof of the Humvee.

Table 17. OSP Data Gathered Summary

ID	OSP-D1 Size (m)	OSP-D2 Time (minutes)	OSP-D3 Time (minutes)	OSP-D4 Fault Time (minutes)	OSP-D4 No-fault Time (minutes)	Science Cycles	OSP-D2+D3+D4 (No-fault) (minutes)
OSPT01	2 x 1.3 x 0.7	6	5 (2 + 3)	41	est. 16	1	27
OSPT06	2.3 x 1.4 x 1.1	6	NA	NA	NA	0	6
OSPT05	25 x 8	2	10 (3 + 3 + 4)	84	est. 25	2	37
OSPT04	5 x 4 x 0.5	4	5 (2 + 3)	45	est. 10	1	19
OSPT03	25 x 20	2	10 (2 + 3 + 3 + 2)	29	est. 17	3	29
OSPT11	250 x 50	2	8 est. 20	NA	est. 30	est. 3	40

3.2.3 Hypotheses and Objectives Discussion

3.2.3.1 Opportunistic science protocol Hypothesis 1 (OSP-H1)

OSP-H1: The amount of time needed to investigate the scientific characteristics of a target of opportunity is in direct proportion to the size of the target.

The hypothesis will be considered true if the following is true:

- There is a function with a least-squares curve fit correlation coefficient greater than 0.90 between OSP-D1 and the sum of OSP-D2 to OSP-D4.

Due to a change in the date of the study, personnel at JSC and the representative of ESA were unable to participate via telecom/WebEx as planned. The science team thus consisted of the four scientists at ARC who participated from the K-10 Control Room.

The original plan was to control all data taking from the K-10 Control Center at ARC using the full planning tools as if the K-10 were still moving under its own control. However, it turned out that the full planning tools were not interacting well with the configuration of the K-10 on the Humvee. Given the limited time to carry out the protocol, we decided to use a special mode of the K-10 that allowed PanCam, Mars Institute (MI), and LIDAR data to be taken in a snapshot mode. It is unclear whether or how the times recorded would have differed if the normal K-10 planning tools had been used.

Figure 38 (note the log scale for size) does not show a linear correlation. However, the data suggest that investigation time does increase with target size. The investigation of boulders OSPT01, OSPT04, and OSPT06 (2.5-m scale targets) took 27, 6, and 19 minutes, respectively, ie, ranged from approximately 0.1 to approximately 0.5 hour. The investigation of ground patches OSPT05 and OSPT03 (25-m scale targets) required 37 and 29 minutes, respectively, ie, ranged from approximately 0.5 to approximately 0.6 hour. The examination of valley head area OSPT11 (250-m scale target) took 40 minutes, ie, approximately 0.7 hour.

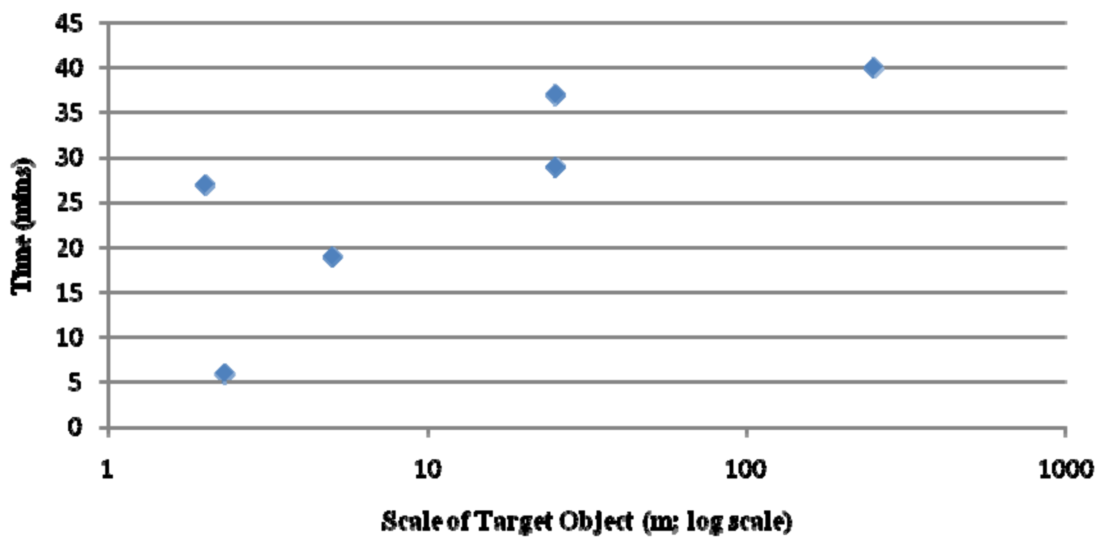

Figure 38. Graph of OSP object size vs. investigation time.

Fitting the data points with a correlation curve is not useful at this stage, as the total number of data points in each size scale remains small, so variance within each size scale is unknown. In the case of OSPT03 and OSPT11, the remote science team indicated that additional time to explore and examine the targets would have also been needed. The total investigation times reported in Table 17 and figure 38 for OSPT03 and OSPT11 therefore represent lower limits.

3.2.3.2 Ground truth assessments

The geological assessments made by the remote science team are summarized in Table 18 (in chronological order), along with ground truth determinations made by Pascal Lee. Table 18 also indicates any significant geological information that was not reported out by the remote science team during its assessments in real time, which might reflect a variety of factors a priori: (a) unfavorable viewing geometry or lighting for imaging, (b) insufficient imaging resolution, (c) perceived time pressure to move on to the next target, (d) focus on other types of geological observations, or e) unfamiliarity with unusual geologic features. Although the science team expressed the need for additional time to characterize two of the largest targets (OSPT03 and OSPT11), all assessments made were generally correct, albeit in some cases incomplete.

Table 18. OSP Ground Truth Assessment

Target	Remote Science Team Assessment Summary	Ground Truth	Significant Observation Not Reported by Remote Science Team	Comments and Lessons Learned
OSPT01	"Object is type carbonate, not breccia. Most likely origin in ice melt from top of hill."	Displaced dolomite (carbonate) boulder exhibiting a variety of surface weathering textural features. Bedding is visible on sides (but not well from initial approach imaging angle).	Bedding in boulder.	Boulder would have warranted closer inspection, but motivation was lacking in initial approach imaging.
OSPT06	"Object is coherent bedded carbonate float from nearby topographic high."	Displaced dolomitic (carbonate) boulder exhibiting a variety of surface weathering	None.	Boulder was well characterized.

Target	Remote Science Team Assessment Summary	Ground Truth	Significant Observation Not Reported by Remote Science Team	Comments and Lessons Learned
		textural features. Bedding is prominent.		
OSPT05	"Polygons apparent in discolored patch. Smaller in size to polygons seen previously, outside of the area. Suggests subsurface ice above 30 cm depth below surface" "Oxidation by discoloration of soil?" "The stained area lies in a slightly lower break in slope, so it is possible that the staining agent pooled in the patch area." "Hydrothermal discoloration apparent on surface of angular carbonate fragments" "Staining appears superficial". "Porous weathering of carbonates" "Botryoidal erosion by hydrothermal processes?" "Hydrothermal discoloration pattern [associated with] polygon edge?"	Orange-colored surface material made of hydro-thermally altered soil and fragmented dolomitic limestone. Periglacial surface sorting has resulted in polygonal-patterned ground. Patch of stained material is located on a topographic saddle, not on a pooling depression.	None.	LIDAR data were deemed not useful by remote science team, possibly because polygon relief was low.
OSPT04	"Fossils present and visible in light gray, angularly fragmented carbonate." "Object in question is a carbonate block."	Low-lying, flat rock slab made of dolomitic limestone. Stromatoporoids and other macroscopic fossils are present. Slab is isolated and likely a drop stone.	No mention of possible origin of this isolated rock slab.	Rock was flat and low-lying enough that additional PanCam imaging was not useful past initial approach image. Rock and fossil identification was made using MI only.
OSPT03	"Object appears to be a patch of large-sized angular fragments with no apparent origin. Paleo-gully? Alluvial wash? More information needed" "[Lidar] evidence suggests presence of subsurface ice in a slight decrease of slope. Slope is indicated by larger polygon size near edges of patch. More investigation needed later for further analysis."	Coarse, boulder-strewn limestone patch resulting from the comminution and break down of a former large limestone mass, probably by gelifraction followed by periglacial creep. Typical downslope deformation of periglacial polygonal patterned ground.	No report of gelifluction (creep) patterns (deformation of polygons downslope).	LIDAR proved very useful in identifying, mapping, and characterizing polygons, possibly because polygons exhibited substantial relief and local slopes. Science team would have liked additional time in which to complete target characterization.
OSPT11	"Fault hypothesis, but results are inconclusive. More investigation needed from multiple angles."	Small glacial trough and meltwater flow valley. Structural control by impact-induced faulting is possible, but not compelling. Debris flows and gullies superposed on valley walls.	Landscape of selective linear erosion, typical of glacial origin for such valleys.	Science team would have liked additional time in which to complete target characterization.

3.2.4 *Opportunistic Science Protocol General Observations and Conclusions*

The above results for the HMP-2010 OSP experiment are consistent to first order with the hypothesis posited, namely that total investigation time required for a target of opportunity will increase with the size scale of the target. This increase does not appear to be in direct proportion to target size as hypothesized, however, but more likely follows an exponential power laws in which the detailed characterization of the largest targets might take considerably more time than that of the smallest ones. Nevertheless, caution must be exercised in interpreting this finding, and no statistically meaningful quantitative relationship can be established yet. The present conclusion suffers in particular from a data set size that remains small – only six targets were examined – and from the fact that the remote science team would have needed more time to complete characterization of at least two of the targets, the largest ones: OSPT03 and OSPT11. While these initial results are promising, they suggest that further iterations of the experiment at this and other analog sites could ultimately yield a more robust quantitative relationship, with appropriate uncertainties bars accounting for important factors such as variations in geologic context, site and material complexity, familiarity with the site and target materials in the context of the region explored, and the payload available for robotic exploration.

3.3 Landing site validation experiment

3.3.1 *Implementation*

The first step in the implementation phase of this experiment was to select a broad area in the general vicinity of the HMPRS within which several alternate landing sites could be located. Terrain characteristics of this general area needed to be diverse within it such that there would be locations that would be successful landing sites as well as locations that would violate Altair landing site criteria. To incorporate the IRG K-10 sensors as part of the simulated robotic sensor suite, and due to known limitations for high-data-rate communications at the HMPRS, the PI selected a 1-km-diameter circle centered on a hill that was part of the IRG "Site A/7" (fig. 13). The center of this circle also became Way Point A for the TRPF experiment.

The PI worked with the Altair Project Office to identify three participants with Altair project experience who became the landing site selection team for this experiment: Brian Derkowski, Doug Rask, and Al Strahan. Members of this team had experience in Altair vehicle design, mission operations, and landing sensors functionality. This team was briefed on the ground rules and objectives of the experiment. Team members were then provided with the data sets described in the protocol. Despite their previous lack of experience with the Google Earth tool, these team members quickly gravitated to this tool with the overlay data sets that were identified for it (eg, NRCan 10-m contour topographic maps).

After examining the features within their assigned 1-km-diameter landing site area, the team settled on a smaller area to the north of the center of the circle. This area appeared to be generally free of surface obstacles and to meet the surface slope constraints. The team then developed a process using PowerPoint to position (laterally and rotationally) a 3×3 "checkerboard" made up of 180-m × 180-m landing squares (fig. 39). The checkerboard center represented the nominal landing site and the eight squares around the center represented alternate/divert landing sites should the crew or lander sensors decide that this nominal site was unsafe during the landing approach phase. Once the planning team was satisfied with the general positioning of the 3×3 checkerboard, team members began to look at the highest resolution imagery available for this area to identify what they considered potential obstacles or hazards. these potential hazards were circumscribed using the same PowerPoint tool to mark their location and indicate the extent of the hazardous area (fig. 40).

After the planning team created a PowerPoint version of the selected landing site and the suspected hazards, this information was mapped into Google Earth so that the data would be available in digital form and as a KML file. The resulting coordinates for the corners of all nine squares (primary landing site square plus the eight surrounding squares) combined are given in Table 19. The table also contains the corner location and bearing for each of the photographs to be taken at the eight primary corners (four corners of the primary landing square and four corners of the entire nine-square grid).

Table 19. LSV Landing Grid Coordinates

ID	Location	Latitude (deg)	Longitude (deg)	Photo Bearing (deg)
LSVCntr	Landing Site	75.452019	-89.888678	N/A
LSVG00	Outer West Corner	75.452198	-89.902330	120 and 73
LSVG01		75.453281	-89.897540	N/A
LSVG02		75.454364	-89.892750	N/A
LSVG03	Outer North Corner	75.455447	-89.887959	210 and 163
LSVG04		75.450995	-89.898018	N/A
LSVG05	Inner West Corner	75.452078	-89.893229	120 and 73
LSVG06	Inner North Corner	75.453161	-89.888439	210 and 163
LSVG07		75.454244	-89.883649	N/A
LSVG08		75.449792	-89.893707	N/A
LSVG09	Inner South Corner	75.450875	-89.888918	343 and 30
LSVG10	Inner East Corner	75.451958	-89.884129	300 and 253
LSVG11		75.453041	-89.879339	N/A
LSVG12	Outer South Corner	75.448589	-89.889397	343 and 30
LSVG13		75.449672	-89.884608	N/A
LSVG14		75.450755	-89.879819	N/A
LSVG15	Outer East Corner	75.451838	-89.875030	300 and 253

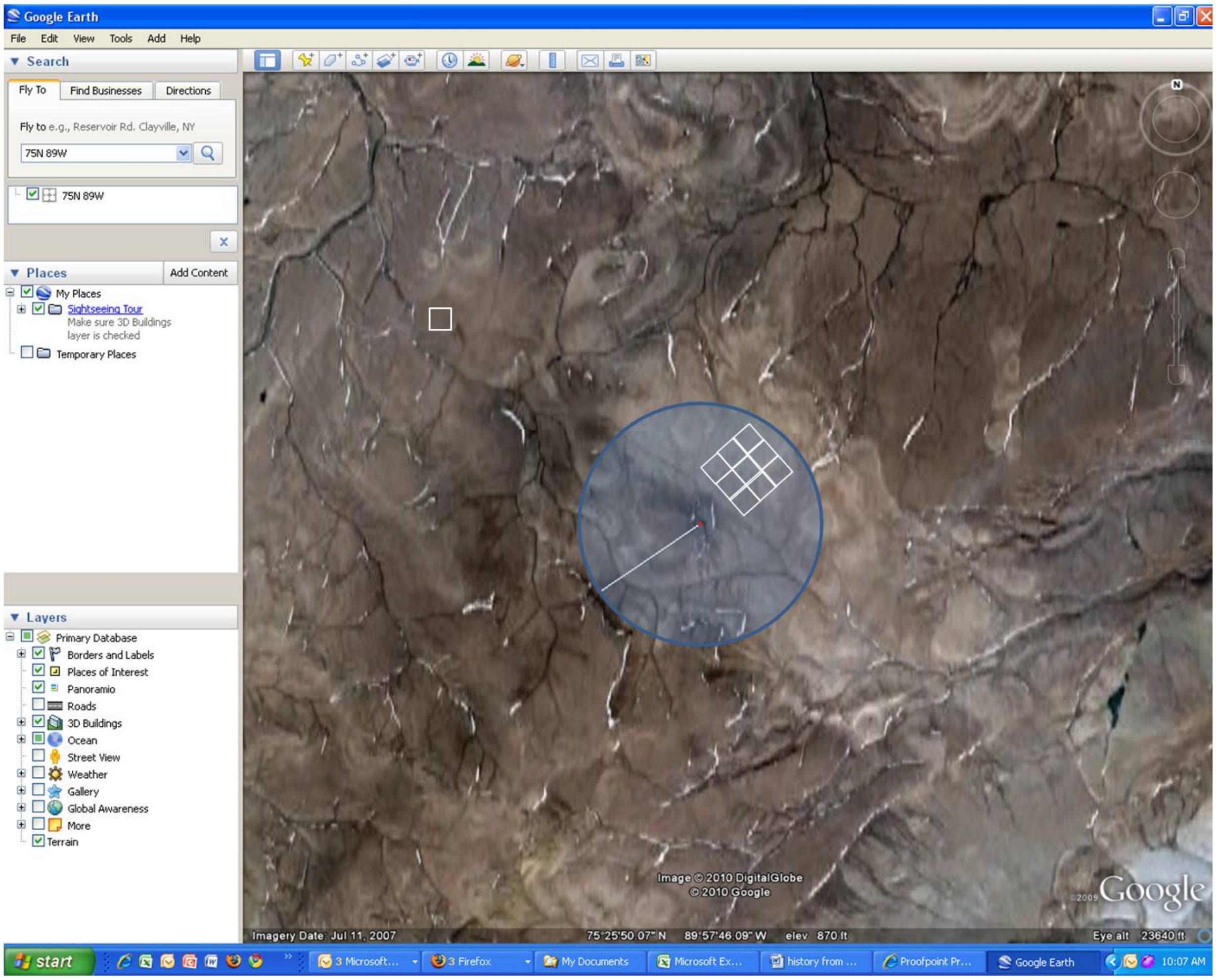

Figure 39. The 3×3 checkerboard location – LSV landing site.

The center of the light blue circle is also Way Point A ("Malapert Massif") in the TRPF experiment.

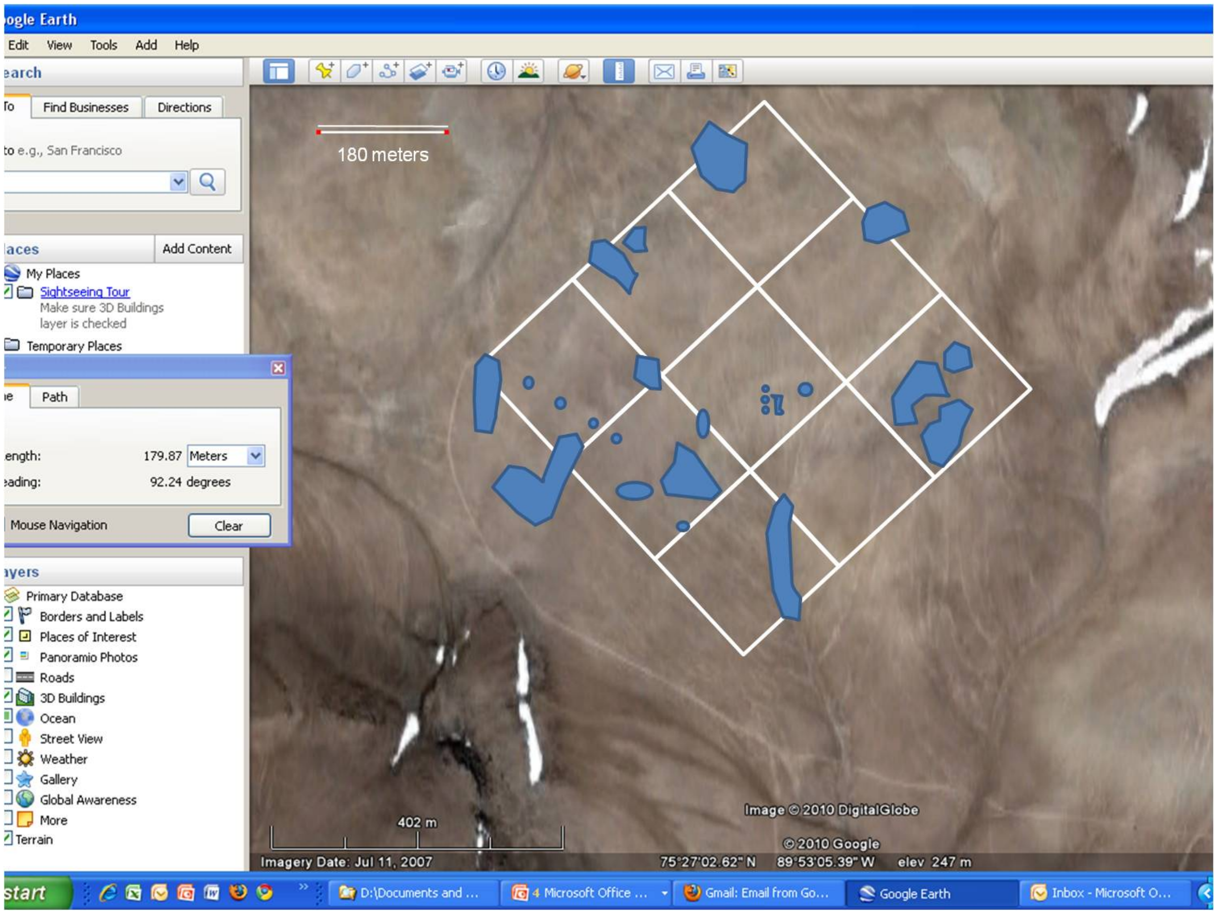

Figure 40. The 3×3 checkerboard with initial hazards.

The blue areas represent the initial list of hazards found from the visual inspection of the Google high-resolution remote observations.

In addition to the hazards the planning team suspected through inspection of the remote observation imagery, the altitude data from Google Earth were extracted on a 10-m grid and slopes were calculated from those data. Additional potential hazard areas were then designated for regions at which the slope was greater than 5 deg (LSVHC25 through LSVHSC29). This grid and the hazards as laid out in Google Earth were shown earlier in figure 7 (blue zones are the remote imagery-derived hazards; yellow zones are the DEM-derived hazards). The centers of each hazard are given in Table 20.

Table 20. LSV Hazard Centers

ID	Latitude (deg)	Longitude (deg)	ID	Latitude (deg)	Longitude (deg)
LSVHC01	75.451877	-89.901806	LSVHC16	75.451755	-89.888123
LSVHC02	75.452010	-89.899762	LSVHC17	75.451625	-89.888105
LSVHC03	75.451751	-89.898268	LSVHC18	75.451684	-89.887510
LSVHC04	75.450864	-89.898710	LSVHC19	75.451874	-89.886123
LSVHC05	75.451508	-89.896604	LSVHC20	75.453931	-89.882137
LSVHC06	75.452126	-89.893822	LSVHC21	75.449788	-89.887542
LSVHC07	75.453761	-89.894343	LSVHC22	75.452230	-89.878594
LSVHC08	75.453485	-89.895488	LSVHC23	75.451858	-89.880763
LSVHC09	75.454774	-89.890144	LSVHC24	75.451341	-89.879094
LSVHC10	75.451306	-89.895523	LSVHC25	75.454111	-89.885561
LSVHC11	75.450650	-89.894691	LSVHC26	75.449637	-89.891955
LSVHC12	75.450815	-89.891958	LSVHC27	75.449979	-89.889383
LSVHC13	75.451487	-89.891221	LSVHC28	75.450384	-89.887145
LSVHC14	75.450209	-89.892295	LSVHC29	75.451847	-89.875610
LSVHC15	75.451897	-89.888071			

In preparation for the real-time portion of the experiment, the planning team decided to develop a qualitative route based on the landing site grid (Table 19) for driving through the landing site area and obtaining additional imagery on the potential hazards the team members had identified from the remote observation data. The proposed route was provided to the PI before he traveled to Devon Island.

On Devon Island, the PI obtained the eight photographs as laid out in Table 19 and examined each of the 25 hazards (LSVH01-LSVH25) detected from remote observation imagery. The location-tagged photographs and the PI ground truth notes were electronically transferred back to the test staff. Due to weather, the PI was unable to complete a detailed analysis of the slopes for LSVH26 through LSVH29; however, he was able to do a quick evaluation and is confident that there were no slopes over 5 deg anywhere within the nine-square landing grid.

While obtaining ground truth information for the landing site, the PI decided to execute the data gathering route that the team had provisionally provided to the PI. Team members had originally planned to modify this route once they had examined the eight primary photos. However, the PI, based on the number of potential hazards and the weather conditions on Devon Island, decided that obtaining the data up front would provide data for a backup plan or could be used as a means by which to reduce execution time of the real-time portion of the experiment.

The day before the planned real-time part of the experiment, the two members of the planning team who were able to participate (remotely from JSC) went through the eight primary photographs under the supervision of the test director (at ARC). The team did not detect any hazards that had not been previously labeled as potential hazards, and found it difficult to judge sizes and distances in the photographs.

Given the projected weather conditions and short time available for the real-time part of the experiment the next day, the PI decided to have the team also review the photographs from the preplanned route. The team reviewed these additional photographs and decided which of the hazards could benefit from further closer views. Again, the team had difficulties determining the size of objects from photographs alone. The

test director observed that the team appeared to find it easier to evaluate the potential hazards with photographs taken at closer distances, less than 50 m, then with the larger-view photos.

The planned real-time part of the experiment was not possible during the time allotted for this experiment due to weather conditions on Devon Island.

After the PI returned to Houston, the entire team was once gathered anew and again went through all of the photographs. The primary purpose for this was to assign a terrain trafficability category to each of the photographs. As was noted for the TRPF team, there was a significant discussion by this LSV team about the size of the area that should be taken into account when assigning terrain zone classifications. For this experiment, the relevant size was basically the size of the lander, about 15 m. Again without direct size and distance indicators in the photographs, the team had a difficult time deciding on the proper categories. When the PI explicitly provided the distance to the object or area of interest, the team quickly converged on categories that were consistent with the opinion of the PI from direct observations. Inclusion of data from a range-finding device, such as the LIDAR instrument used on the K-10 rover and originally planned for this experiment, would probably have overcome this limitation.

3.3.2 Data Gathered

Table 21 and the rest of this section summarize the data gathered to evaluate the hypotheses and form the basis of the observations and conclusions given in later sections.

Table 21. LSV Data Gathered Summary

ID	Description	Value
LSV-D1	Number of hazards identified using remote data.	Total 29 From imagery 24 From DEM 5
LSV-D2	Number of additional/unidentified hazards identified using simulated robotic sensors.	0
LSV-D3	Number of hazards identified by ground truth assessment that are not identified in LSV-D1 or LSV-D2 (performed by personnel on site at Devon Island only).	0
LSV-D4	Ground truth notes and assessment (eg, zone classifications) of all surface hazards in the designated landing area (Note: Ground truth notes and assessments performed by personnel on site at Devon Island; LSV team also performs zone classification using still images.)	See notes following this table

Data summary for LSV-D4:

- Ground truth data indicated only one of 24 hazards as an actual hazard (as defined by the Altair Project). This was due to multiple rocks (all under 1.4 m) and a slight slope.
- Detailed measurements of the slope for LSVH25 were not accomplished. Slope measurements were made in the LSVH26-LSVH29 areas, and all were found to be less than 3.0 deg. A qualitative inspection of the entire area by the PI also indicated no areas of concern due to slopes.
- A comparison of the team's terrain category evaluations and that of the ground truth by the PI are in agreement, once the problems with size and distance judgments are taken into account (see observations and discussion in conclusions).

3.3.3 Hypotheses and Objectives Discussion

3.3.3.1 Landing site validation hypothesis 1

LSV-H1: The remote observation data sets available are sufficient for planning primary landing sites.

The hypothesis is considered to be true if all of the following are true:

- LSV-D2 is zero.
- LSV-D3 is zero.
- LSV-D4 assessments indicate that the landing site selection team correctly interpreted the surface features indicated in the remote observation data.

As both LSV-D2 and LSV-D3 are zero, the truth of the hypothesis lies with the evaluation of LSV-D4 for remote observation data. The landing site selection team correctly interpreted the non-hazards areas as non hazards, and sufficient non-hazard areas (one primary and one alternate clear landing area) were within their selected 3×3 "checkerboard" landing site; thus, LSV-D4 and the hypothesis are considered true for this location.

With respect to this hypothesis, additional thought may need to be given to creating a related hypothesis or criteria concerning the observed tendency of this LSV planning team to be overly conservative (as indicated by ground truth observations) in the identification of potential hazards. In this particular case, only one of the 29 identified potential hazards could have been considered a hazard.

3.3.3.2 Landing site validation hypothesis 2

LSV-H2: Landing sites selected using remote observation data can be validated using robotic scout capabilities.

The hypothesis will be considered true if all of the following are true:

- LSV-D3 is zero.
- LSV-D4 assessments indicate that landing site selection team correctly interpreted the surface features indicated in the robotic sensor data.

As LSV-D3 is zero, the truth of the hypothesis lies with the evaluation of LSV-D4 for robotic observation data. The landing site selection team correctly interpreted the non-hazards areas as non hazards, and sufficient non-hazard areas (one primary and one alternate clear landing area) were within their selected 3×3 "checkerboard" landing site; thus, LSV-D4 and the hypothesis are considered true for this location.

Similar to the observation about LSV-H1, there is a corresponding question about over-conservatism that will probably need to be addressed in the future. For the robotic observations, this was additionally complicated by the difficulty the team had determining sizes and distance from photographs alone. This probably would have been mitigated for the robotic observations had the real-time portion of the experiment taken place. If this portion of the LSV experiment had taken place, the LIDAR would have provided distance and size information. In a worst-case situation, the team could have driven up to the object or area in question, and the combination of multiple photographs at different distances would have given the team members sufficient information.

3.3.4 Landing Site Validation Conclusions and General Observations

During the execution of this experiment and the analysis and discussion of the data from it, we made the following observations and came to the following conclusions:

- The remote observation data were sufficient to pick an adequate landing site within the Altair constraints at this location (LSV-H1).

- Surface-level imagery significantly improved our understanding of the selected landing site and the nature of the potential hazards; one primary and one alternate landing site could have been validated at this location (LSV-H2).

The team and the PI also made a number of general observations.

- While both the hypotheses were shown to be true, the more general observation is that the principal values of the hazard identification exercise entailed locating a large landing area that was probably safe and therefore worthy of further examination, and mapping out which features the robotic scout needed to examine.
- The team was very conservative in its identification of potential hazards. Only one of the 29 hazards identified by the team was even likely to be of significant concern. Given that the height of individual obstacles could not be determined from remote data, this should have been expected. The team could identify clumps of rocks, but could not determine their height from remote data. Further iterations of this experiment should investigate the inclusion of a hypothesis or other evaluation criteria that take into account "over-conservatism" in identifying potential hazards and/or additional data or methods (eg, shadow analysis) to determine some level of height information in remote observations.
- It was difficult for the team to accurately judge sizes and distances in surface imagery. There is a definite need for additional size and distance queues in the photographs taken as part of the scouting function or for range-determining sensors (eg, a LIDAR) to be included (see discussion in the last item of this list).
- It was virtually impossible for the team to accurately judge slopes in the surface imagery. In addition to the information needed to determine sizes and distances, some indication needs to be provided of local horizontal.
- The usefulness of terrain classification for landing site evaluations was unclear. Further discussion should take place on the size of the area to which the criteria should be applied – the size of the entire landing square or just the size of the lander. Once size and distance queues are taken into account and assuming the robot observations include a direct slope measurement, terrain classifications from the robotic observations match the ground truth.
- As the real-time part of this field test did not take place, LIDAR was not used. It had been assumed that LIDAR would provide sufficient additional size and distance information; however, later experience during OSP indicated that such tools were not necessarily available for real-time operations (a consequence of the specific LIDAR data display implementation used for the IRG K-10 operations). This last point needs be addressed before a repeat of the experiment.

3.4 Experiment results summary and lessons learned

We developed six hypotheses that we could test in the field for the three experiments conducted this year. Of these hypotheses, data collected indicated that four were true, one was not true, and one was not tested (directly) due to resources and time constraints. All of these conclusions are made with caveats that were discussed in details in previous sections; a brief summary for each hypothesis is provided below.

One observation that was made in all of these experiments is the need for cues within the imagery to assist users in determining size, distance, and slope for the terrain that appears in the image.

A lesson learned during the traverse experiment, but that has implications in all of the experiments, is the use of planning tools that can integrate the various data sources and other meta-data used to provide planners and operators with better situational awareness as they plan or execute their tasks.

3.4.1 Traverse Route Planning and Following Conclusions and General Observations

During the execution of this experiment and the analysis and discussion of the data that were derived from it, we made the following observations and came to the following conclusions regarding the three hypotheses developed for this experiment:

- (TRPF-H1) The remote observation data are insufficient to plan a definitive route; that is, completely free of undetected obstacles that would stop vehicles of the type assumed in this experiment. However, while the remote observation data were marginal for detection of obstacles such as rocks, no sections were impassable due to rocks alone.
- (TRPF-H2) Surface-level imagery provided a significant improvement in our knowledge of the route and was required to complete the traverse. All major obstacles were identifiable in the surface-level imagery. Some of marginal cases were not immediately seen, but likely would have been detected had real-time, full-motion surface-level imagery been available. As with the remote observation data, determination of slopes was the most difficult problem to detect and evaluate.
- (TRPF-H3) The original proposed field test was not implemented due to insufficient resources and time in the field. However, using some limited opportunistic data, it appears there is a concern that it may take too long for the "drivers" to correlate multiple views. Additional work needs to be done on exactly how multiple views would be used and how the imagery can be quickly correlated. But, given the results from this opportunistic experiment, any additional work in this area should be considered low priority.

3.4.2 Opportunistic Science Protocol General Observations and Conclusions

The above results for the HMP-2010 OSP experiment are consistent to first order with the hypothesis posited (OSP-H1), namely that total investigation time required for a target of opportunity will increase with the target size scale. Caution must be exercised in interpreting this finding, however, and no statistically meaningful quantitative relationship can be established yet. These initial results are promising, and suggest that further iterations of the experiment at this and other analog sites should ultimately yield a robust quantitative relationship, with appropriate uncertainties bars accounting for important additional factors such as variations in geologic context, site and material complexity, and payload available for robotic exploration.

3.4.3 Landing Site Validation Conclusions and General Observations

During the execution of this experiment and the analysis and discussion of the data derived from it, we made the following observations and came to the following conclusions:

- (LSV-H1) The remote observation data were sufficient to pick an adequate landing site within the Altair constraints at this location.
- (LSV-H2) Surface-level imagery significantly improved our understanding of the selected landing site and the nature of the potential hazards; one primary and one alternate landing site could have been validated at this location.

The team and the PI also observed that while both of the hypotheses were shown to be true, the more general observation is that the principal values of the hazard identification exercise were in locating a large landing area that was probably safe and, therefore, worthy of further examination, and in mapping out which features the robotic scout needed to examine.

4. Appendices

4.1 Appendix A: Study hardware

The characteristics of the major hardware used during the experiments are described in the following sections.

4.1.1 Small Pressurized Rover Analog

A Humvee Rover will be used for detailed observations planned by the OSP team and the LSV team. The vehicle characteristic most pertinent for OSP as well as for LSV is the height above the surface. The ground rules for impassable terrain (slope, object size) that can be negotiated by this SPR analog will be ruled on by the PI at the sites in question. The SPR analog is shown in figure 41.

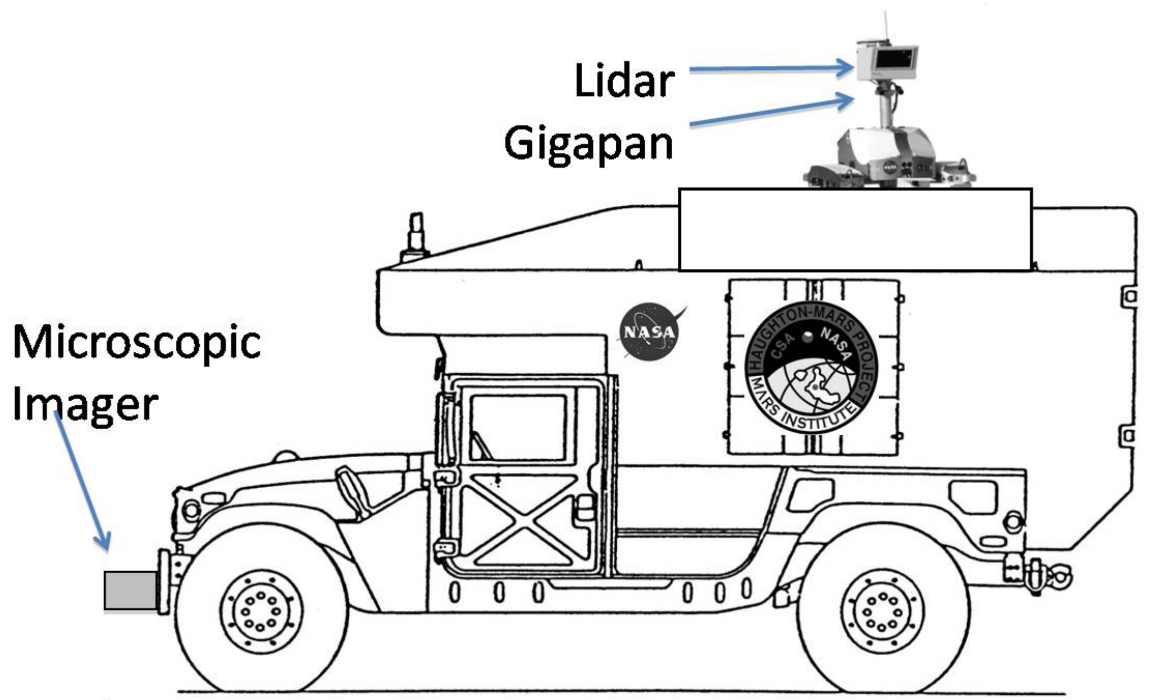

Figure 41. SPR analog

Note that the microscopic image was moved to the rear bumper in a last-minute configuration change.

For purposes of the experiments in this protocol, no effort will be made to convert this Humvee for robotic operation. A human operator in the Humvee will instead execute simple voice commands delivered via a voice link between this operator and the remotely located team “driving” the SPR analog. Data from the sensor suite will be acquired either through remote activation of the sensors (while this is the preferred approach, as of the time at which this document was prepared this option has yet to be confirmed) or by a second human operator manually activating the sensors. These returned data will be the only means by which the remote operators will know whether their commands have been executed to their specification. If required, additional voice commands will be sent to the Humvee driver; the driver will not respond directly to the remote operators.

For the purpose of this experiment and potential future use, MI (John W. Schutt) designed and built a multi-part steel crane structure (fig. 42) to easily hoist/remove and mate/de-mate the K-10 to/from the roof rack of the Humvee.

Figure 42. Crane used to load K10.

Figure 43. Microscopic imager.

The microscopic imager was located on the rear bumper of the Humvee for the OSP experiment.

4.1.2 Microscopic Imager

The microscopic imager (a Cannon PowerShot G9 digital camera; 4000×3000 pixels) provides high-resolution, close-up, color terrain views at 72 microns per pixel (fig. 43). The camera, which was mounted on the rear bumper of the Humvee for the OSP experiment, can be used for close-up imaging of the surface and small objects.

4.1.3 Light Detection and Ranging

The LIDAR has a 40×40-deg FOV for a single scan and has three resolution modes: High = 390 urad (0.41 m [1.34 ft]), Medium = 780 urad (0.82 m [2.68 ft]), and Low = 1560 urad (1.63 m [5.36 ft]). As the LIDAR is being used in close proximity to the objects during the OSP and due to available bandwidth, we expect to use only the low-resolution setting with a single scan. The LIDAR will remain mounted to the K-10 unit, and the entire unit will be place on the Humvee Rover.

4.1.4 Gigapan

The Gigapan can take panoramic images by automatically pointing a mounted camera and stitching together the images. A 12M pixel camera will be mounted to the Gigapan. The default setting for the FOV of a single photograph will be 40 (TBR – camera dependent) × 30 deg (horizontal × vertical) with an image size of about 5.2MB. Depending on the selection by the planning group at each location along the traverse, it is expected that either a 3×1 (120×30-deg) or 2×1 (80×30-deg) mosaic will be obtained. During the OSP, the Gigapan will remain mounted to the K-10 unit and the entire unit will be placed on the Humvee Rover.

- Weight: 3.3 kg (7.25 lbs) with battery
- Size: 27.12 × 30.25 × 15 cm (10-5/8 × 11-7/8 × 5-7/8 in.)

The digital camera mounted in the Gigapan system (fig. 44) is the same type as that used for the TRPF experiment; it is described in the next section.

Figure 44: Gigapan system with camera.

Figure 45: Canon PowerShot SX 110 IS.

4.1.5 Digital Camera

Still images were gathered using a digital camera. The camera was mounted on a walking stick so that all photographs for the TRPF and LSV experiments were gathered at about eye level. For the OSP experiment, the camera was mounted in the Gigapan system described in the previous section.

The camera chosen for this task was the Canon PowerShot SX110 IS (fig. 45). This is a compact digital still camera with a built-in flash, and 10× Optical/4× Digital/40× Combined Zoom with an optical image stabilizer system. Other camera characteristics are as follows:

- Manufacturer/Model: Canon PowerShot SX110 IS
- Image Capture Device
  - Type: 9.0 Megapixel, 1/2.3-in.-type charge coupled device (CCD)
  - Total Pixels: Approximately 10.3 Megapixels
  - Effective Pixels: Approximately 9.0 Megapixels
- Lens
  - Focal Length: 6.0-60mm f/2.8-4.3 (35mm film equivalent: 36-360mm)
  - Digital Zoom: 4×
  - Focusing Range:
    - Normal: 1.6-ft/50-cm-infinity (W), 3.3 ft/1-m-infinity (T)
    - Macro: 0.39 in.-1.6 ft/1-50 cm (W)
  - Autofocus System: TTL [through the lens] Autofocus
- Maximum Aperture: f/2.8 (W) – f/4.3 (T)
- Shutter Speed: 15-1/2500 sec (settable in Tv and M)
- Storage Media: SD/SDHC Memory Card, MultiMediaCard, MMC Plus Card, HC MMC Plus Card
- File Format: Design rule for camera file system, DPOF [digital print order format] Version 1.1
- Image Compression: Normal, Fine, SuperFine
- JPEG [Joint Photographic Experts Group] Compression Mode: Still Image: Exif 2.2 (JPEG)
- Dimensions (W×H×D): 4.35 × 2.77 × 1.76 in./110.6 × 70.4 × 44.7 mm
- Weight: Approx. 8.64 oz/245 g (camera body only)
- Operating Temperature: 32-104°F/0-40°C

4.1.6 Digital Angle Meter

Ground truth slopes will be measured using a digital angle gauge. This device will be mounted to the vehicle that is used for gathering slope and other field data (most likely an ATV). The angle gauge will be mounted to this vehicle in such a way as to measure the slope in the direction of travel of this vehicle.

The digital angle gauge chosen for this task was the Wixey WR-300. This device has the following characteristics:

- Manufacturer/Model: Wixey WR-300
- Range: ±180 deg
- Resolution: 0.1 deg
- Accuracy: ± 0.1 deg
- Repeatability : ± 0.1 deg
- Size: 5.1 × 5.1 × 3.3 cm (2 × 2 × 1.3 in.)
- Battery: 3.0 V CR2032

This device has a pair of magnets to allow it to be fixed securely to a metal surface, although additional measures will be used to secure this to a vehicle that is moving. It has a ZERO button to calibrate the angle gauge to any reference surface, and will then measure angles relative to that reference.

Figure 46. Wixey model WR-330 digital angle gauge.

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13. ABSTRACT *(Maximum 200 words)*

The field tests documented in this report examine one facet of a larger program of planetary surface exploration that has been evolving and maturing for several years, growing from a broad policy statement with a few specified milestones for NASA into an international effort with much higher-fidelity descriptions of systems/operations necessary to accomplish this type of exploration. The ISECG Reference Architecture is neither a lunar base nor a series of Apollo-style missions. It employs a flexible approach to lunar exploration that can accommodate changes in technologies, international priorities, and programmatic constraints as necessary. It relies on NASA Constellation architecture for crew and large-cargo transportation but is robust to variations (increases or decreases) in landed mass. It shows flexibility, and redundancy will be improved by using small cargo launch vehicles to deliver scientific payloads and logistics (eg, laboratory/excavation equipment and crew support items). The Architecture is composed of phases that will deploy a range of international human-rated and robotic technologies over time on the lunar surface. And, it will provide continuous robotic and human exploration activity in multiple locations on the Moon: the robotic precursor phase, polar exploration and system validation phase, polar relocation phase, and nonpolar relocation and long-duration phase.

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